A METHODOLOGY TO DEVELOP AN INTEGRATED ENGINEERING SYSTEM TO ESTIMATE QUANTITIES FOR BRIDGE REPAIRS AT THE PRE-DESIGN STAGE

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A METHODOLOGY TO DEVELOP AN INTEGRATED ENGINEERING SYSTEM TO ESTIMATE QUANTITIES FOR BRIDGE REPAIRS AT THE PRE-DESIGN STAGE

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To My Family

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Alternating Current
ACI	American Concrete Institute
CER	Cost Estimating Relationships
CoRe	Commonly Recognized Structural Elements
CP	Cathodic Protection
CW	Crack Width
DC	Direct Current
DoE	United States Department of Energy
DOT	Department of Transportation
EGS	Emergency Gas Supply
EPT	External Post Tension
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FRP	Fiber Reinforced Plastic
FSW	Feet of Seawater
IGPT	Internal Grouted Post Tension
IUPT	Internal Ungrouted Post Tension
MHT	Maximum High Tide

MLE	Material, Labor and Equipment
MLW	Mean Low Water
MR&R	Maintenance, Repair and Rehabilitation
NBI	National Bridge Inventory
NBIS	National Bridge Inspection Standards
NSF	National Science Foundation
OMT	Ontario Ministry of Transportation
OSHA	Occupational Safety and Health Administration U.S. Department of Labor
Q1	First Quartile
Q2	Second Quartile
Q3	Third Quartile
QVD	Quantitative Damage Values
SQL	Structured Query Language
USDOT	United States Department of Transportation

SUMMARY

This research presented a methodology to integrate the existing Pontis™ database with detailed bridge inspection data, repair guidelines, heuristics, construction processes and rules in order to generate material, labor and equipment (MLE) quantities that could be applied against current cost data to reflect the cost of repairing highway bridges without using 100 percent design documents. The scope of the research was limited to concrete bridge piles in a marine environment. The considered repair technology knowledge was related to cathodic protection jackets with either sacrificial zinc mesh or titanium impressed current and all polymer encapsulation. The type of damage considered was reinforcement corrosion and unsound concrete. The Florida Department of Transportation (FDOT) provided damage and construction data. While the experimental data relate specifically to FDOT, the research findings and conclusions may be extended to all states that use Pontis™ since each collects and maintains inspection data that are based on nationwide guidelines set to "increase uniformity and consistency of inspections" (Hartle et al. 1990).

A Damage Assessment Model, Construction Process Model and Parametric Quantity Model were developed with the purpose of capturing the engineering knowledge involved in the estimating process of bridge repair construction projects.

The Damage Assessment Model was used to create a sample database in which detailed inspection data were stored in a format compatible with the existing Pontis™

database. Detailed inspection data, which provided quantitative values for the different damage types observed in bridges, could be retrieved from the sample database so that data could be used as either input parameters in the knowledge rules that triggered the selection of construction tasks in the Construction Process Model, or data could be used as variables in the equations used to estimate quantities in the Parametric Quantity Model.

The Construction Process Model incorporated the logic behind the construction process for different repair methods. The Construction Process Model was composed of seven repair matrices that defined specific repair methods for each Pontis™ bridge element. Construction tasks were grouped in construction modules that were modeled as flowcharts. Each construction module flowchart was composed of construction tasks arranged in sequential order and decision points that triggered the selection of construction tasks based on input parameters and knowledge rules. Input parameters were provided by the user, retrieved from the model or pre-defined in the model by expert knowledge. The construction modules developed involved construction tasks related to the repair of concrete bridge piles that were damaged due to reinforcement corrosion and related concrete deterioration. Data describing the construction tasks that were considered in the construction module flowcharts were modeled using the entity-relationship model and were stored in the sample database described previously. Such data were retrieved from the sample database because they were required by the Parametric Quantity Model in order to select the quantity items that had to be estimated for the construction tasks selected.

The Parametric Quantity Model combined data generated by the Damage Assessment Model and the Construction Process Model with additional expert knowledge and parameters into equations that were used to estimate quantities.

The analysis of damage data from detailed inspection reports demonstrated that the data, which described concrete deterioration, that is spall width, length and depth as well as crack length, showed defined normal distributions for each Pontis™ Condition State. Therefore, it was possible to define damage default values for each Pontis™ Condition State using quantitative terms, based on the mean values and ranges observed for each damage parameter. The analysis of detailed inspection data and as-built data also demonstrated that actual damage quantities were larger than those defined by detailed inspection reports.

Neural network results were combined into dynamic probability trees to estimate actual damage quantities from detailed inspection reports. Such dynamic probability trees were a tool to estimate actual damage quantities based on inspection data, specifically volume of concrete to be removed, and both transverse and longitudinal reinforcement replacement due to corrosion damage. The available data used by the neural network were limited to individual bridges and referred to damage above the water.

Important contributions of the research were to associate Pontis™ Condition States to quantitative values and specific damage definition and to provide a methodology to collect and maintain detailed inspection data in an electronic format, so that such data could be later incorporated into the estimating process.

Another contribution was to provide a methodology to define specific construction tasks and MLE quantities for a given bridge and its selected repair method instead of the generic Pontis™ Maintenance, Repair and Rehabilitation actions. MLE quantities could be applied against current data to generate a cost estimate. A methodology that defines construction tasks and MLE quantities at the pre-design stage and that is based solely on bridge inspection data and the system knowledge base could improve project definition and result in potential savings.

Finally, the statistical analysis of the collected data provided a range of values to estimate the amount of damage characteristic to each Pontis™ Condition State when detailed inspection data were not available. The use of neural networks provided a framework to estimate the actual existing damage in the bridge. Estimating the actual damage in the bridge may reduce project uncertainties. This research also provided a methodology to identify and estimate factors that affect labor productivity as demonstrated by a preliminary survey conducted among Navy Divers, which included labor productivity factors and duration of underwater construction activities.

CHAPTER I

INTRODUCTION

1.1 Purpose and Objectives

The goal of this research was to provide the methodology to design an integrated engineering system that could be used to estimate the material, labor and equipment (MLE) quantities required to repair concrete bridge piles in a marine environment. This methodology could be used to integrate repair guidelines, heuristics, construction processes, rules, existing databases and the system knowledge base. An engineering estimating system as opposed to a historical cost estimating system has the capability to generate material, labor and equipment in engineered quantities that can be later applied against current cost data to reflect the cost of repairing highway bridges.

To accomplish this goal, the research had the following specific objectives:

1. Prove that detailed inspection data could be stored in a database that was compatible with the existing Pontis™ database maintained by state departments of transportation.
2. Define the amount and type of damage existing in a bridge using quantitative damage values.
3. Expand the Pontis™ Condition State definitions by describing the damage on the element using specific and quantitative terms for each type of damage.

4. Define specific repair options for each bridge element defined in the Pontis™ database.
5. Locate and collect the current technology knowledge and regulations used to repair concrete bridge piles. This objective required interviews with experts, knowledge of current accepted engineering practices, understanding of governing design codes and analysis of actual design specifications for repair alternatives.
6. Define construction tasks required to repair concrete bridge piles.
7. Model the logic behind the construction process for different repair methods for concrete bridge piles.
8. Select construction tasks based on bridge site-specific data and quantitative damage values.
9. Estimate MLE quantities for the construction tasks selected.
10. Review and assess the existing, federally owned PACES bridge models and develop specific engineering algorithms to augment the PACES bridge models.

The engineering system developed was composed of a Damage Assessment Model, a Construction Process Model and a Parametric Quantity Model. The Damage Assessment Model estimated the amount and type of damage existing in the bridge using quantitative terms. It allowed the describing of different types of damage for each element. It also provided a methodology to generate default values for the parameters describing the damage. The construction processes model incorporated the logic behind the construction process for different repair methods and defined construction tasks required based on bridge site-specific conditions. The Parametric Quantity Model combined data generated by the Damage Assessment Model and the construction processes model with additional expert knowledge to calculate quantities for repair.

Using the methodology it was possible to incorporate site conditions and construction sequencing specific to each bridge repair estimate. Site conditions have a considerable effect on the repair project, yet they are not considered when collecting or using traditional historical data to make estimates at the pre-design stage.

As a research baseline, this researcher used the Florida Department of Transportation (FDOT) because data were readily available and were representative of other state Departments of Transportation (DOT's) specifications. To illustrate the models developed, the methodology was applied to define material labor and equipment quantities required for the repair of bridge piles using cathodic protection (CP) jackets with sacrificial anode mesh.

1.2 Description of the Problem

Existing estimating methods required complete construction documents to define accurate material, equipment and labor quantities. Quantity take-off estimating methods required 100% complete construction documents to produce an accurate estimate and to define the construction tasks involved.

Estimates that are produced at the pre-design stage are not accurate. Based on data provided by state officials, Anderson (2001) stated that there was an 80% increase of cost before construction. He attributed this lack of accuracy to the fact that initial estimates:

> “Are based on a “rough footprint” that identifies the type of highway or bridge and the number of lanes and interchanges and are rough estimates based on historic per-mile costs and square footage costs for that state. Also costs increase during the design process as preliminary design concepts refined into detailed plans and specifications.”

To improve the initial estimate, Anderson (2001) recommended that the cost-estimating engineer and/or the consultant:

> “Do a more detailed project design at the environmental phase. While this approach removes some of the uncertainties that can only be addressed through the detailed design stage, it more likely would not be feasible for many projects because of the cost. Further, this approach can work at cross purposes with an environmental process that seeks to see all alternatives equally considered.”

Thus, there is a need to improve the accuracy of estimates at the pre-design stage, which allows analyzing different alternatives without placing a large workload on state employees. Traditional methods of estimating compared only quantities and resulting costs to make decisions. The construction process was not included until complete construction documents were generated. This lack of consideration of the construction process forced the making of decisions to be based on the cost of materials and not on construction methods.

Currently, 38 State DOTs establish their budget needs using Pontis™, a bridge management system. Efforts that were aimed to establish a cost database for Pontis™ Bridge Management System demonstrated that there were large standard deviations for maintenance, repair and rehabilitation costs for some bridge elements (Cobb 1995). In this case, the collected cost data were based on bid quantity item, often called “pay items," and expert knowledge. Bell (1987) stated that using historical "pay items," data might result in inaccurate estimates, and stated that:

> "A contractor may deliberately unbalance the bid and in doing so might either quote a very low or very high unit for the selected pay items..…If an estimator uses this unit price to prepare a preliminary estimate for a future project, the preliminary cost estimate would either be too high or too low and hence unrealistic. It can be concluded, therefore, that using the unit price for the dominant material quantity would not always lead to a realistic and reliable estimate."

The practice of intentionally unbalancing pay items might explain the large standard deviations for maintenance, repair and rehabilitation costs observed by Cobbs (1995).

In addition, as stated by Smith (1999), cost of bridge maintenance should not be based on average values obtained from historical data since:

> "This practice can induce serious errors because it does not consider that many costs are related to the physical characteristics of the bridge."

Using current estimating methods in bridge repair projects, the cost-estimating engineer had to deal with unknown quantities, such as the amount of unsound concrete in the bridge or the amount of reinforcement corrosion. These unknown quantities could not be defined until the repair project started and concrete was removed from the element to expose the damage. Therefore, contracts were based on open quantity items that were paid in full at the end of the project based on as-built quantities. Uncertainty in material quantities and in project costs produced inaccurate estimates and prevented the efficient use of available funds for bridge repair. There was also a lack of historical data on new repair methods, making it extremely difficult to estimate quantities at the pre-design or decision phase using traditional estimating approaches.

Also, a lack of historical data along with a lack of consistency among repair projects due to unique conditions encountered on each individual bridge repair project made it difficult to use regression analysis techniques to estimate costs.

States are reluctant to use regression models that are based on a limited number of projects and out-of-state data. As an example, according to Turochy (2001), Virginia DOT found that a regression analysis parametric cost estimating model was not applicable to Virginia because the data were from Michigan. Another concern was the limited number of project samples used. Turochy (2001) discussed that “with only 18 projects, the range of data may not fully address the range of projects found in Virginia.”

Bridge repair is unique in the sense that there might be countless damage types, let alone bridge element types, that are required to define the damage in the bridge, which might result in the selection of different construction tasks for each one of the bridge elements considered within the same quantity estimate. Therefore, a new methodology that incorporates a relational database with the capability to handle different values for the same input parameter throughout the estimating process is required.

1.3 Scope of the Research

The research scope was limited to bridge repair and specifically to concrete bridge piles in a marine environment. Bridges that were used to develop the models were those maintained by the FDOT. The scope included repair technology knowledge related to cathodic protection jackets with either sacrificial zinc mesh or titanium impressed mesh and all polymer encapsulation. The types of damage considered were reinforcement corrosion and unsound concrete. Damage data included in the research were provided by bridge inspection reports and as-built reports from the FDOT. Construction sequencing implemented in the model was based on guidelines recommended by the FDOT, as shown in design plans and construction documents analyzed. Outside the scope of the research were the following:

1. Implementation of an automated prototype model.
2. Software development.
3. Design of a complete knowledge base for all bridge elements.
4. Population of a complete knowledge base for all bridge elements.
5. Incorporation of deterioration models to estimate repair costs at different stages of the life of the structure.
6. Incorporation of probabilistic models such as Monte Carlo simulations.

1.4 Research Benefits

Providing a methodology to collect and maintain detailed inspection data in an electronic format would permit the incorporation of such data in the decision-making and estimating process. The new methodology will allow for a more fundamental understanding of the parameters that drive cost. This will lead to better design, maintenance and life cycle decisions.

Incorporating the knowledge that is used to design a repair into the cost estimating methodology would provide a decision-making methodology similar to the one used by the design engineer to define the tasks required to repair the bridge. The main benefit of the research would be the ability to define construction tasks at the pre-design stage for the unique physical condition of the bridge that either would not be defined until a detailed design is completed or could not be defined by a regression analysis model due to the lack of historical data. Thus, at the pre-design stage, the new methodology could be used to fill the information gap between no design and the detailed design, since such a detailed design would most likely not be produced at such an early stage of the project.

Being able to identify construction tasks at the pre-design stage by modeling the logic behind the construction process for different repair methods would improve the project definition at the early planning stages of the project, would improve the accuracy of estimates at the pre-design stage, and would reduce the workload burden on state employees.

By making the data design compatible with the existing Pontis™ database, the 38 states that currently use Pontis™ would be able to associate the current Pontis™ Condition State that are assigned to bridge elements to specific damage values. Therefore, the methodology incorporates the Pontis™ database to facilitate the implementation, if any, of the methodology through state DOTs.

Implementation of the methodology developed in this research by state DOTs might result in consistency of repair quantity data among the states and allow sharing of construction data on new repair technology. The designed system would provide an efficient tool to estimate quantities at the project level that in turn would result in confidence in project definition and cost. The time required to generate cost estimates, once quantities are defined, would be minimized resulting in potential time and money savings. For individual construction project managers, the integrated engineering system might provide the assessment technology to conduct value engineering on capitalintensive infrastructure renewal solutions. The system might allow project managers to understand and evaluate the construction process, material, labor and equipment requirements of repair projects.

For the construction industry, the integrated engineering system might provide a thorough and consistent assessment technology for handling complex decisions and for estimating infrastructure repair. A work breakdown structure and consistent approach to establishing engineering requirements for repair technologies and materials might have a cost-saving potential.

1.5 Organization of the Thesis

This thesis was organized in nine chapters. Chapter I provides an introduction to the research, describes the problem and discusses the research scope and objectives. The Background Chapter (Chapter II) presents the point of departure or the existing knowledge in the research areas.

The methodology used during the research is summarized in Chapter III. The development of the Damage Assessment Model is described in Chapter IV; the Construction Process Model is described in Chapter V and the Parametric Quantity Model in Chapter VI. Data collected is analyzed and discussed in Chapter VII. A validation of the models is presented in Chapter VIII. Conclusions and recommendations are made in Chapter IX.

Sample bridge inspection reports and as-built reports were provided by FDOT, they are listed in Appendix A, but they are shown because they are not releasable since 9/11/2001 based on Florida Statute 119.07 (3)(ee). Documents are on file in researcher's office and FDOT. The Microsoft Access® queries used in the Damage Assessment

Model are presented in Appendix B. Repair matrices for other bridge elements are presented in Appendix C. Construction tasks, knowledge rules and the Microsoft Access® queries used in the Construction Process Model are presented in Appendix D, E and F respectively. The Microsoft Access® queries used in the Construction Process Model are presented in Appendix G. Sample equations and knowledge rules used in the Parametric Quantity Model are discussed in Appendix H. Results and analysis of the survey to determine duration of construction tasks are presented in Appendix I. A typical questionnaire used in such a survey is shown in Appendix J. Construction data collected during field observation are included in Appendix K. Validation and results data are presented in Appendix L. FDOT Project plans and quantity computation book related to the validation example are listed in Appendix M, but they are not shown because they are not releasable since 9/11/2001 based on Florida Statute 119.07 (3)(ee). Documents are on file in researcher's office and FDOT is shown in Appendix M.

CHAPTER II

BACKGROUND

2.1 **Introduction**

This chapter presents the point of departure or the existing knowledge in the following research areas: bridge management, repair technology, estimating principles, data modeling and data analysis. The significance of each one of the topics to the research is described in Figure 2.1. Bridge inspection and the Pontis™ bridge management system are the two components of bridge management discussed as they are related to the development of the Damage Assessment Model in Chapter IV. Repair technology refers to concrete and reinforcement repair guidelines, repair system technology included in the scope of this research and design plans provided by FDOT, all of which were used in the development of the Construction Process Model in Chapter V. Traditional methods of cost estimating are also discussed, as well as the PACES estimating software.

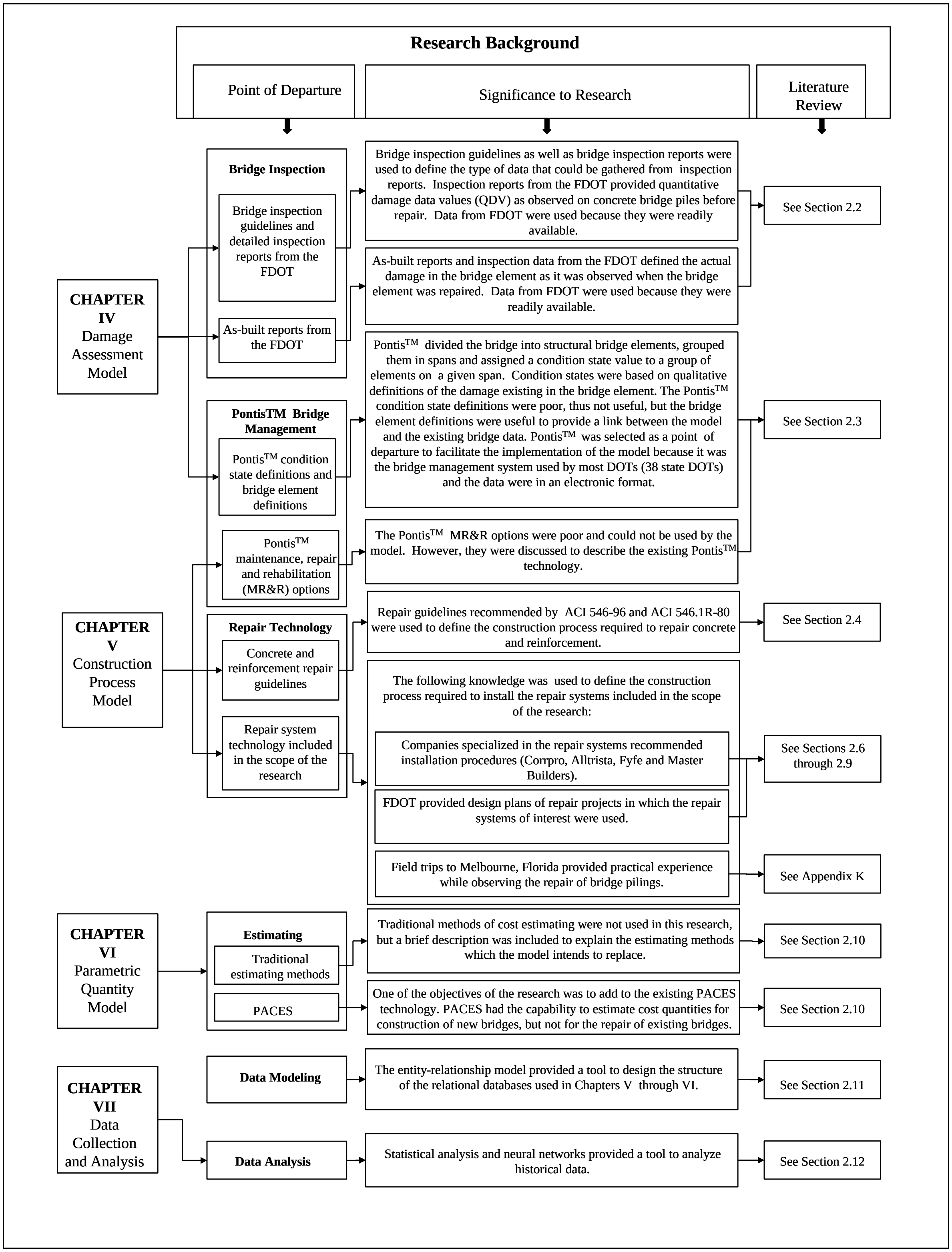

Figure 2.1 Research Background

2.2 Bridge Inspection

This section describes inspection reports and the type of data that is recorded on them. According to the American Association of State and Highway Transportation Officials (AASHTO) (1983):

> "Bridge inspection is the use of techniques and a plan intended to determine and maintain a record of the physical condition of a bridge and its site".

The National Bridge Inspection Standards (NBIS) (1988) mandated recording the findings and results of bridge inspections on standard formats, which were called bridge inspection reports. Hartle et al. (1990) on *The Bridge Inspector's Training Manual*, published by the FHWA discussed the significance of inspection data:

> "Guidelines for inspection ratings have been refined to increase uniformity and consistency of inspections. Data from bridge are critical input into a variety of analyses and decisions by state agencies and the Federal Highway Administration".

According to Hartle et al. (1990), bridge inspection reports "provide useful information on the needs and effectiveness of routine maintenance activities".

Inspection reports should contain detailed data of the damage existing on bridge elements as discussed herein. While inspecting a bridge, Hartle et al. (1990) recommended identifying damage in the bridge element by their specific type. Typical damages observed in concrete elements are listed in Table 2.1.

Table 2.1 Typical Damages Observed on Concrete Bridge Elements

Damage Type	Damage Description	Parameters Describing the Damage
Cracks	"A crack is a linear fracture in concrete. Cracks may extend partially or completely through the concrete member" (Hartle et al. 1990).	Record the width and length of the crack as well as the location and orientation (Hartle et al. 1990).
Scaling	Scaling is "the gradual and continuing loss of surface mortar and aggregate over an area". Severe scale might result in loss of coarse aggregate as well (Hartle et al. 1990).	Record the size of the area, the depth of penetration and the location of the damage (Hartle et al. 1990).
Delamination	"Delamination is an area of concrete which gives off a hollow sound when struck with a hammer, indicating the existence of a fracture plan below the surface which will lead to a spall" (Hartle et al. 1990).	Record the width and length of the delamination as well as the location of the damage (Hartle et al. 1990).
Spalling	A spall is a horizontal fracture of the concrete caused by the expansion of corrosion of the reinforcement steel or by friction from thermal movement. (Hartle et al. 1990).	Record the size of the area, the depth of penetration and the location of the damage (Hartle et al. 1990).
Chloride Contamination	"Chloride contamination is the presence of recrystalized soluble salts…evidenced by dirty-white surface deposits called efflorescence" (Hartle et al. 1990).	To determine the chloride content, concrete testing using cores from the element may be required according to ASTM C114 or AASHTO T260 (Kostmatka 1988). Record the value of acid soluble chloride content. Values greater than 0.20% by mass of cement correspond to the chloride threshold to depassivate embedded steel and permit corrosion (OMT S0-88-7 1996).
Honeycomb	"Honeycombs are hollow spaces in the concrete caused by concrete having segregated so badly that there is very little sand and cement to fill the gaps between the coarse aggregate particles" (Hartle et al. 1990). "Honeycombs are caused by improper vibration during location" (Hartle et al. 1990).	Record the size of the area and the location of the damage (Hartle et al. 1990).
Pop-outs	"Pop-outs are conical fragments that break out of the surface of the concrete leaving small holes. Pop-outs are caused by reactive aggregate and high alkali cement". They are also caused by aggregate, which expand with moisture (Hartle et al. 1990).	Record the size of the area, the depth of penetration and the location of the damage (Hartle et al. 1990).
Collision Damage	Collision damage is caused when vehicular or marine traffic strikes the bridge element (Hartle et al. 1990).	Record the size of the area, the depth of penetration, and the location of the damage. Physical tests may be required to determine the extent of damage (Hartle et al. 1990).
Abrasion	Abrasion is the erosive action of sand and silt suspended in water on concrete surfaces exposed to wave action (Hartle et al. 1990).	Record the size of the area and the location of the damage (Hartle et al. 1990).
Overload Damage	"Overload damage or serious cracks may occur when concrete members are overstressed" (Hartle et al. 1990).	Note any excessive vibration or deflection. Physical tests may be required to determine the extent of overstress (Hartle et al. 1990).
Reinforcing Steel Corrosion	"Corrosion is the loss of member material", and spalls and cracks in concrete " (Hartle et al. 1990).	"Section loss should be reported as a dimensional quantity relative to cross sectional thickness" (Hartle et al. 1990). Corrosion activity can be measured by a corrosion potential survey in accordance with ASTM C876-91 (OMT SO-88-7 1996). Corrosion is associated to the potential measured as follows (OMT SO-88-7 1996): Less than (–0.20V) indicate 90% probability that corrosion is not occurring. In the range (-.20V to -.35V) corrosion is uncertain. Greater than (-.35V) indicate 90% probability that corrosion is occurring (-0.35V).

Hartle et al. (1990) recommended recording the type, quantity and location of the damage in the inspection report. As an example, for spalling and scaling he recommended to record the size of the area and the depth of penetration of the damage. For crack damage, Hartle et al. (1990) recommended recording the length and width of the crack.

FDOT (1970) used two parameters to characterize crack damage: (1) crack length and (2) crack class. The crack class was a scale based on the crack's width (CW):

$$\mathrm{CLASS} = 1 \text{ if } 0 < \mathrm{CW} < 1/64 \text{ inch}$$

$$\mathrm{CLASS} = 2 \text{ if } 1/64 \text{ inch} \geq \mathrm{CW} < 1/32 \text{ inch}$$

$$\mathrm{CLASS} = 3 \text{ if } 1/32 \text{ inch} \geq \mathrm{CW} < 1/16 \text{ inch}$$

$$\mathrm{CLASS} = 4 \text{ if } 1/16 \text{ inch} \geq \mathrm{CW} < 1/8 \text{ inch}$$

$$\mathrm{CLASS} = 5 \text{ if } \mathrm{CW} \geq 1/8 \text{ inch}$$

Hartle et al. (1990) also recommended defining the location and orientation of each element. He suggested using span numbers and bay numbers to identify general areas of the bridge. Also, he proposed to identify sides of the elements with near/far, north/south or east/west designations.

According to Hartle et al. (1990), the information contained in inspection reports might be supplemented by reference to "as-built" plans and documents. The author revised as-built reports prepared by the FDOT. Such as-built reports recorded the actual volume of concrete removed and reinforcement repaired during a bridge repair project.

2.3 Pontis™ Bridge Management System

Thirty-eight state DOTs use Pontis™ (Small 1999). Pontis™ was developed following the FHWA Demonstration Project 71 (O' Connor et al. 1989). Pontis™ was developed as a bridge management system and assessment technology through which bridges were selected for critical improvements and repair. According to Small (1999), Pontis™ used a "top down" approach in which budgets and standards were used to develop optimal policies which were then used to plan projects. As discussed in the *Pontis™ Technical Manual* (Pontis™ 1997), Pontis™ utilized element condition ratings, mathematical modeling of element deterioration (Markovian process), direct unit costs, and project scheduling based on budget constraints. Through Pontis™, physical bridge inspection data were recorded, element deterioration was predicted and a projected cost for a suggested maintenance repair and rehabilitation project (MR&R) was provided (Pontis™ 1997).

The objective of the Pontis™ bridge management system was to suggest the most cost-effective combination of bridge MR&R projects for a set of bridges over a multi-year planning horizon. Pontis™ was designed to manage a statewide combination at the total program level (Pontis™ 1997).

Pontis™ divided the bridge in structural elements. Structural elements were defined according to the ASSHTO *Guide for Commonly Recognized (CoRe) Structural Elements* (ASSHTO 1997). CoRe elements were classified by material. Table 2.2 lists the bridge substructure CoRe elements used in Pontis™. The bridge elements included in the scope of the research are shown highlighted.

Pontis™ grouped elements of the same type according to the span in the bridge where they were located. For vertical elements, such as concrete piles, Pontis™ did not define bents. In a bridge, bents could be located either at the beginning or at the end of the span.

Table 2.2 Substructure CoRe Elements

CoRe Element	Steel Unpainted	Steel Painted	Prestressed Concrete	Reinforced Concrete	Timber
Column or Pile Extension	201	202	204	205	206
Pier Wall	NA	NA	NA	210	NA
Abutment	NA	NA	NA	215	216
Submerged Pile Cap or Footing	NA	NA	NA	220	NA
Submerged Pile	225	NA	226	227	228
Pier Cap	230	231	233	234	235
Culvert	240	NA	NA	241	242

(AASHTO 1997, pp 18). Note: (NA stands for Not Applicable)
(Used by Permission of AASHTO)[1]

In Pontis™, all bridge elements could have up to five condition states characterizing the physical condition of the element (some had less; concrete pile had four). Each element condition state combination was termed a condition unit (Pontis™

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[1] From *ASSHTO Guide for Commonly (CoRe) Structural Elements*, 1997, by the American Association of State Highway and Transportation Officials (ASSHTO), Washington, D.C. Used by permission. AASHTO publications may be purchased from the organization's bookstore at 1-800-231-3475 or online at http://bookstore.transportation.org.

1997). Condition state definitions were those provided in the *Guide for Commonly Recognized (CoRe) Structural Elements* (ASSHTO 1997).

Existing condition unit quantities were entered into the program manually as part of a bridge inspection record. For concrete bridge piles, Condition State 1 was optimal condition and Condition State 4 was worst condition. Condition was expressed as a quantity of the element in each of four possible condition states. For example, of 48 reinforced concrete columns of a bridge, 36 might be in Condition State 1, 12 might be in Condition State 3 and none might be in Condition States 2 and 4. Each condition state had at most three MR&R action options as defined in the *Guide for Commonly Recognized (CoRe) Structural Elements* (ASSHTO 1997). An element in Condition State 4 may have options similar to “replace unit”, “rehab unit” or “do nothing”; while an element in Condition State 1 may only have the option of “do nothing.”

All substructure prestressed concrete elements had common condition state descriptions and feasible actions (AASHTO 1997) as listed in Table 2.3. Similarly, with the exception of the reinforced concrete culvert, all the substructure reinforced concrete elements had common condition state descriptions and feasible actions (AASHTO 1997), as listed in Table 2.4. Definitions for reinforced concrete elements were similar to those for prestressed concrete elements; one referred to mild steel reinforcing bars and the other to prestressed strands. Definitions provided in Table 2.3 and 2.4 were copied textually from the *Guide for Commonly Recognized (CoRe) Structural Elements* (ASSHTO 1997).

Table 2.3 Condition State Descriptions and Feasible Actions for Substructure Prestressed Concrete Elements

Condition State	Condition State Description	Feasible Actions
1	"The element shows little or no deterioration. There may be discoloration, efflorescence, and or superficial cracking but without effect on strength and/or serviceability" (AASHTO 1997).	"-Do nothing" (AASHTO 1997).
2	"Minor cracks or spalls may be present, and there may be exposed reinforcing with no evidence of corrosion. There is no exposure of the prestressed system" (AASHTO 1997).	"-Do nothing -Seal cracks and minor patching" (AASHTO 1997).
3	"Some delamination and/or spalls may be present. There may be minor exposure but not deterioration of the prestressed system. Corrosion of non-prestressed reinforcement may be present, but loss of section is incidental and does not significantly affect the strength and/or serviceability of either the element or the bridge" (AASHTO 1997).	"-Do nothing -Clean steel and patch (and/or seal)" (AASHTO 1997).
4	"Delaminations, spalls, and corrosion of non-prestressed reinforcement are prevalent. There may also be exposure and deterioration of the prestressed system (manifested by loss of bond, broken strands or wire, failed anchorages, etc). There is sufficient concern to warrant an analysis to ascertain the impact on the strength and/or serviceability of either the element or the bridge" (AASHTO 1997).	"-Do nothing -Rehab unit -Replace unit" (AASHTO 1997).

Table 2.4 Condition State Descriptions and Feasible Actions for Substructure Reinforced Concrete Elements (With the Exception of Reinforced Concrete Culverts)

Condition State	Condition State Description	Feasible Actions
1	"The element shows little or no deterioration. There may be discoloration, efflorescence, and/or superficial cracking but without effect on strength and/or serviceability" (AASHTO 1997).	"-Do nothing" (AASHTO 1997).
2	"Minor cracks or spalls may be present, but there is no exposed reinforcing or surface evidence of rebar corrosion" (AASHTO 1997).	"-Do nothing -Seal cracks and minor patching" (AASHTO 1997).
3	"Some delamination and/or spalls may be present and some reinforcing may be exposed. Corrosion of rebar may be present, but loss of section is incidental and does not significantly affect the strength and/or serviceability of either the element or the bridge" (AASHTO 1997).	"-Do nothing -Clean rebar and patch (and/or seal)" (AASHTO 1997).
4	"Deterioration is advanced. Corrosion of reinforcement and/or loss of concrete section is sufficient to warrant analysis to ascertain the impact on the strength and or serviceability of either the element or the bridge" (AASHTO 1997).	"-Do nothing -Rehab unit -Replace unit" (AASHTO 1997).

Pontis™ assigned a direct unit cost for each MR&R action on a condition unit. Functional unit cost estimates were used to define the total cost by multiplying the direct unit cost by the corresponding quantity of the element to be repaired or replaced. Default direct costs were updated through historical project cost data or expert elicitation (Pontis™ 1997). In the historical project cost data process, the costs of previously completed actions were used to develop a new direct cost. The total cost of each MR&R action was calculated by multiplying the direct unit cost of each MR&R action by the number of elements to receive the action. The total project cost was the sum of all

MR&R action direct costs and the project indirect cost (Pontis™ 1997). The cost matrix used by Pontis™ to estimate the cost of MR&R actions referred to an element-condition state-environment-action. As an example, the cost to repair a prestressed concrete column that was severely damaged and was in a marine environment was $200.00 per lineal foot. This unit price was the same for a pretension or a post-tension column and was the same for all possible repair methods. The unit price was the same for all possible types of severe damage such as corrosion or sulfate attack, and was the same for all bridges. This type of gross unit price estimating did not provide different costs for all the different possibilities.

2.4 Repair Technology for Concrete Bridge Piles

This section is a background review on concrete repair technology and on repair and protection methods that have been used or proposed in literature for bridge piles. The scope of this research was limited to concrete and reinforcement deterioration due to reinforcement corrosion. When corrosion occurs, concrete surrounding the reinforcement breaks and needs to be removed. Thus, the repair of a concrete pile usually includes removing unsound concrete, repairing the reinforcement and preparing the pile surface to receive new grout. Once the pile has been repaired, protection systems can be installed on the pile to prevent further deterioration. Some of the protection systems include Cathodic Protection (CP). Protection systems discussed in this research are summarized as follows:

1. Integral CP jacket with sacrificial anode mesh.
2. Integral CP jacket with impressed current anode mesh.

3. All polymer encapsulation.
4. Hybrid fiber epoxy composites.

There is a section, beginning at Section 2.6, for each type of protection system mentioned in the above list. Each section includes a description of the system and the installation procedure. Thaesler (2005) discussed concrete and reinforcement repair guidelines, which are presented in Sections 2.4.1 to 2.4.3.

2.4.1 Concrete Removal

Quantity estimates reviewed by the author were based on the dimensions of existing deteriorated concrete areas. The width, length, and depth of such areas were recorded on detailed bridge inspection reports. In some cases, the depth of deteriorated concrete to be removed was assumed to be at least the dimension of the reinforcement cover. As-built reports reviewed by the author indicated that concrete areas that show cracks were removed, but it was not clear which crack parameters dictated the removal of concrete. The author did not find in the literature review any study that correlated concrete deterioration inspection data such as spall and crack dimensions with the volume of concrete removed after repairing the deteriorated concrete area.

Following are guidelines provided by the American Concrete Institute (ACI) to remove deteriorated concrete.

1. Remove all concrete that shows evidence of active or potential corrosion. Such areas are usually larger than the area of spalled or delaminated concrete according to ACI 546.1R (1980). Thus, an approved method to determine areas

where steel reinforcing is actively corroding is to measure the electrical potential using a copper-copper sulfate half-cell.

2. Use a pneumatic concrete chipper, sand blaster or water blaster to remove unsound concrete. Eighty pounds should be the maximum weight of the hammer (ACI.1R 546, 1980). After removing the larger areas of unsound concrete, a smaller chipping hammer should be used. Chipping hammers are typically used above water with water blasters used underwater. Micro cracking of the concrete surface is common when impact tools are used. Micro cracking may weaken the bond between the existing pile and the new grout. Sand and water blasting are less violent methods of concrete removal, and they may be more appropriate (ACI 546R, 1996).
3. Use gad points rather than chisel points because they leave a rougher surface. Use of chisel points may contribute to the propagation of existing cracks (ACI 546.1R, 1980).
4. Remove concrete to create a clear space of 6 mm plus the dimension of the maximum aggregate size of the repair material behind the reinforcing bar when removal of the material has exposed more than half of the perimeter of the reinforcing bar. Extreme care should be taken to prevent damage of reinforcement (ACI 546R, 1996).
5. Flush repair area with high-pressure water to remove loose particles after removal of unsound concrete (ACI 546.1R, 1980).

2.4.2 Reinforcement Repair

Reinforcing steel and prestressing steel are the two types of flexural reinforcement used in concrete structures. Prestressing steel is either bonded or unbonded. Bonded prestressing steel is either pretensioned or post tensioned (grouted). Unbonded steel is post tensioned. Shear reinforcement is used in conjunction with flexural reinforcement. Stirrups are a common type of shear reinforcement used in concrete bridge piles. Stirrups are flat rings that can be closed around flexural reinforcement.

Unlike concrete, reinforcement is not visible unless it is exposed when loss of concrete cover occurs due to deterioration. Detailed inspection reports should list the location of exposed reinforcement and the percentage of cross section loss (Hartle et al. 1990). The author did not find in the literature review any study that correlated reinforcement deterioration inspection data with the quantity of reinforcement repaired.

Repair of reinforcement includes the following steps:

1. Removal of concrete surrounding steel. A pachometer is required to determine the location and depth of the reinforcement to prevent accidental damage of reinforcement during concrete removal.
2. Cleaning reinforcing steel. All loose mortar, rust, oil and other contaminants should be removed from all the exposed surface of the reinforcement. Abrasive blasting is the most common method to clean reinforcement. Abrasive blasting includes sandblasting and high-pressure water blasting (ACI 546R-96).
3. Repair reinforcement. There are two repair options for reinforcing steel: replacement or supplementing. Replacement of mild reinforcing bars consists

of cutting the damage area and splicing in replacement bars (ACI 546R-96). Pretensioned bonded strands cannot be re-tensioned. Substitute strands can be provided externally (ACI 546R-96). Unbonded post tensioned strands are installed inside sheathings that are embedded in the concrete. A portion of the strand can be replaced by cutting the sheathing to expose the strand. The strand is cut on each side of the deteriorated zone, and the deteriorated strand is removed. A new section, spliced at the location of the cuts, replaces the section of the existing strand that is removed. The strand is then re-tensioned (ACI 546R-96). The strand can be completely removed and replaced by a similar one, or a new strand with a smaller diameter but a greater strength material can be inserted in the sheathing and re-tensioned to provide a stressing force comparable to that of the original strand (ACI 546R-96).

2.4.3 Concrete Surface Preparation

Proper concrete surface preparation is critical to improve the performance of the repair. According to ACI 546R-96, "the repair will be only as good as the surface preparation, regardless of the nature, sophistication, or expense of the repair material" (ACI 546R-96). Surface preparation should include the following:

1. Remove concrete as indicated above.
2. Repair reinforcement as indicated above.
3. Flush repair area with high-pressure water, sandblast or vacuum clean area to remove loose particles after removal of unsound concrete (ACI 546.1, 1980).

2.5 Repair System for Concrete Bridge Piles

The repair systems considered in this section included:

- Integral CP Jacket with Sacrificial Anode Mesh
- Integral CP Jacket with Impressed Current Anode Mesh
- All Polymer Encapsulation
- Hybrid Fiber Epoxy Composites

A CP system prevents corrosion by supplying electrons to the structural elements to be protected. Metal corrosion is suppressed when electrons are supplied to the structure. Electrons can be provided by impressed current or by galvanic coupling.

The first system discussed is a galvanic system in which a metal of higher potential like zinc provides the current. The second system is an impressed current CP in which an external power source provides the current delivered.

Both systems consist of a mesh supported by a reinforced fiberglass jacket. The jacket is filled with cement grout. The metal mesh, either titanium or zinc, becomes the anode. The reinforcing steel becomes the cathode. The electrical connection between the anode and cathode is called the negative connection and must be installed with the system. The electrolyte is the concrete pile, new grout and flowing water. The electrolyte is in contact with both the cathode and the anode. The four elements required for corrosion, which are cathode, anode, electrical connection and electrolyte are present. Corrosion occurs, but in this case the corroding metal is not the steel. Rather it is either the zinc mesh or the activated titanium mesh, which constitutes the anode. Steel is protected by converting it into a cathode.

The success of this method requires all reinforcement to be electrically continuous and the negative connection to remain in place. On prestressed piles, current procedures to insure continuity include connecting a steel wire between continuous and discontinuous strands.

2.6 Integral Cathodic Protection Jacket with Sacrificial Anode Mesh

An integral jacket with a zinc sacrificial mesh is a CP system used to prevent corrosion of the reinforcement on concrete bridge piles. Figure 2.2 (a) shows a three dimensional view of a galvanic system composed of a jacket with a sacrificial zinc anode, and Figure 2.2 (b) shows a two dimensional view. Each component of the jacket is labeled in both Figure 2.2 (a) and (b). These components are:

A. Zinc negative connection to the prestressed steel strands

B. Expanded zinc anode placed inside the fiberglass jacket

C. Wired connection to the zinc mesh

D. Fiberglass jacket filled with sand-cement grout

E. Cast bulk zinc anode (shown in Figure 2.2 (b) only)

The bulk zinc anode protects the piling in the tidal zone. Use of this anode prevents the premature consumption of the mesh anode (Powers 1994).

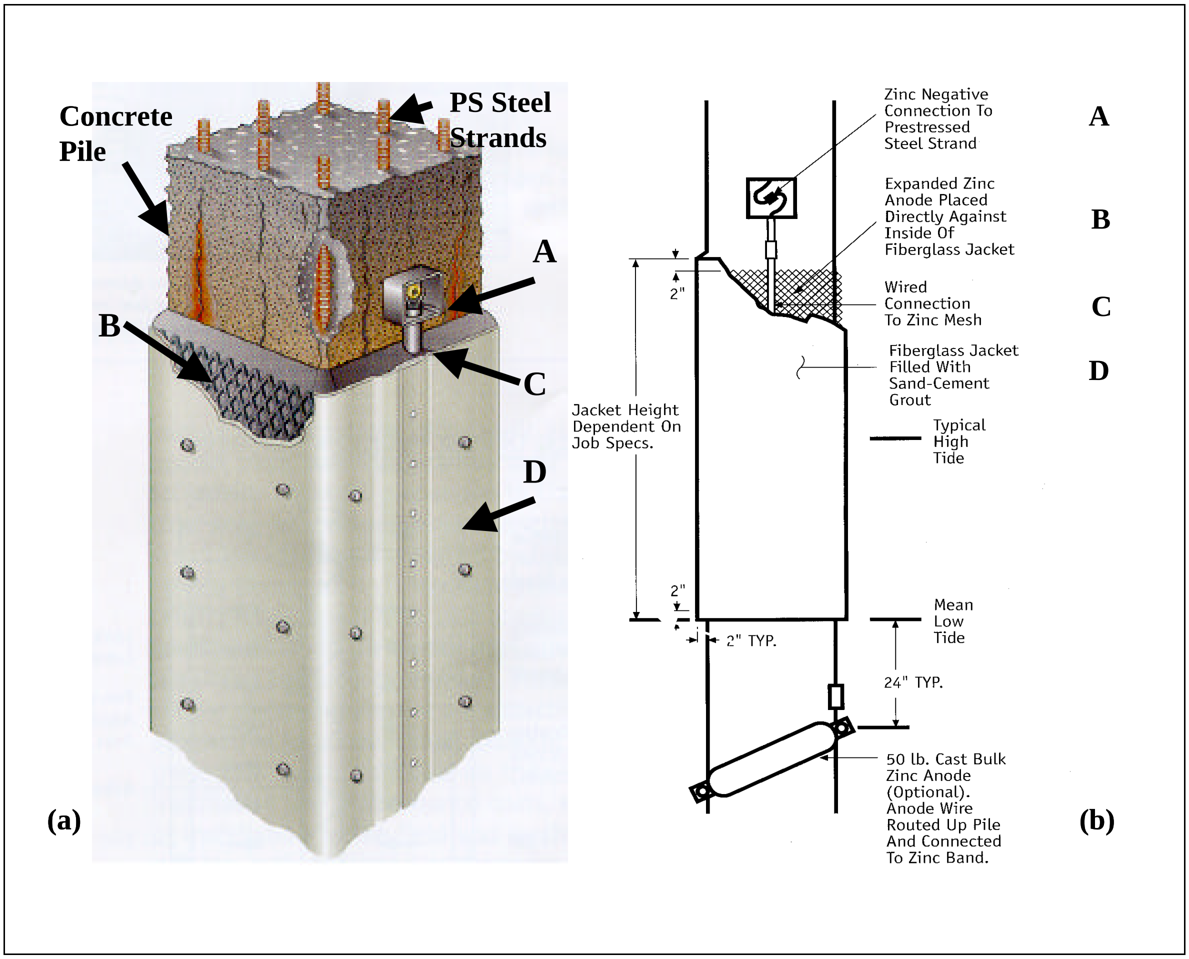

Figure 2.2 (a) 3-D View of an Integral CP Jacket with Sacrificial Node Mesh (b) 2-D View of the Jacket

(Used by permission of Alltrista Zinc Products Company, Lifejacket® Figures have been modified)

The integral CP jacket with a zinc sacrificial mesh was tested on two substructure pilings of the Broward River Bridge located on State Road 105 in Jacksonville, Florida (Rogers 1993). The bulk zinc anode was installed at an elevation of two feet below low tide and an electrical connection was routed to the reinforcement.

2.6.1 Installation Procedure

Typical installation procedures used by the FDOT are described below:

1. Survey piles to determine low tide elevation.
2. Clean pile surfaces within limits of new jackets of all unsound concrete, marine growth and other deleterious materials.
3. Sandblast exposed steel to a “near white” condition.
4. Repair or replace reinforcement as required.
5. Check for electrical continuity of reinforcement.
6. If reinforcement is not electrically continuous, make it continuous.
7. Install reference cell.
8. Attach a 50-pound anode to the pile at correct elevation and route the wiring to junction box location.
9. Attach friction type collars or bottom formwork to piles to maintain jacket at correct elevation until grout placement. Friction collars and formwork are not shown in Figures 2.1 (a) and (b), and they are not permanent components of the system. They are removed after grout reaches its final set.
10. Place pile jacket forms around the pile and securely fasten in place.

11. Ensure at least a two-inch separation between reinforcing steel and the mesh to allow for placement of the grout.
12. Place lateral formwork, external bracing, banding or clamps around the jacket to keep it square and in place.
13. If there is water in the jacket, remove water from jackets and rinse the pile with fresh water immediately prior to placement of grout.
14. Mix a custom blended grout mix with potable water on site.
15. Cast grout in the bottom 6 inches of the jackets to provide a seal if needed.
16. Pump grout into the forms. Pumping shall be accomplished by placing the hose from the top and withdrawing it as the concrete level rises.
17. Remove all formwork, friction type collars, external bracing and banding when the grout has reached its final set (approximately 24 to 48 hours), and clean the jacket of any spilled filler material.

2.7 Integral Cathodic Protection Jacket with Impressed Current Anode Mesh

Impressed current anodes work similarly to sacrificial zinc anodes. The main difference is that zinc sacrificial anodes use galvanic current which is generated naturally when the zinc and steel electrodes are connected, while the impressed current uses current provided in the system by external alternating current (AC) and a rectifier. Drawings of a typical jacket were provided by the FDOT but they are not releasable since 9/11/2001 based on Florida Statute 119.07 (3)(ee). Pictures are on file in FDOT and researcher's office (FDOT (a)).

The system is very similar to the CP jacket with sacrificial zinc anodes. The impressed current jacket does not require a bulk zinc anode, but it requires an insulated titanium current distributor, which is welded to the titanium mesh at the factory.

2.7.1 Installation Procedure

Typical installation procedures used by the FDOT are described below:

1. Follow steps 1 to 7 described in the standard installation procedure of the CP jacket with sacrificial zinc anodes.
2. Follow steps 9 to 17 described in the standard installation procedure of the CP jacket with sacrificial zinc anodes.
3. Connect conductor bars to the low maintenance Direct current (DC) source.

2.8 All Polymer Encapsulation

Snow (1996) described a polymer encapsulation system that used translucent jackets. A typical jacket is shown in Figure 2.3. According to Snow (1996), the rigid translucent fiberglass reinforced polymer jackets have the following features:

1. They are made of a laminate of glass woven roving and mat.
2. They are impregnated with a clear UV light stabilized polyester resin.
3. They come with grout injection ports and integral overlapping seams.

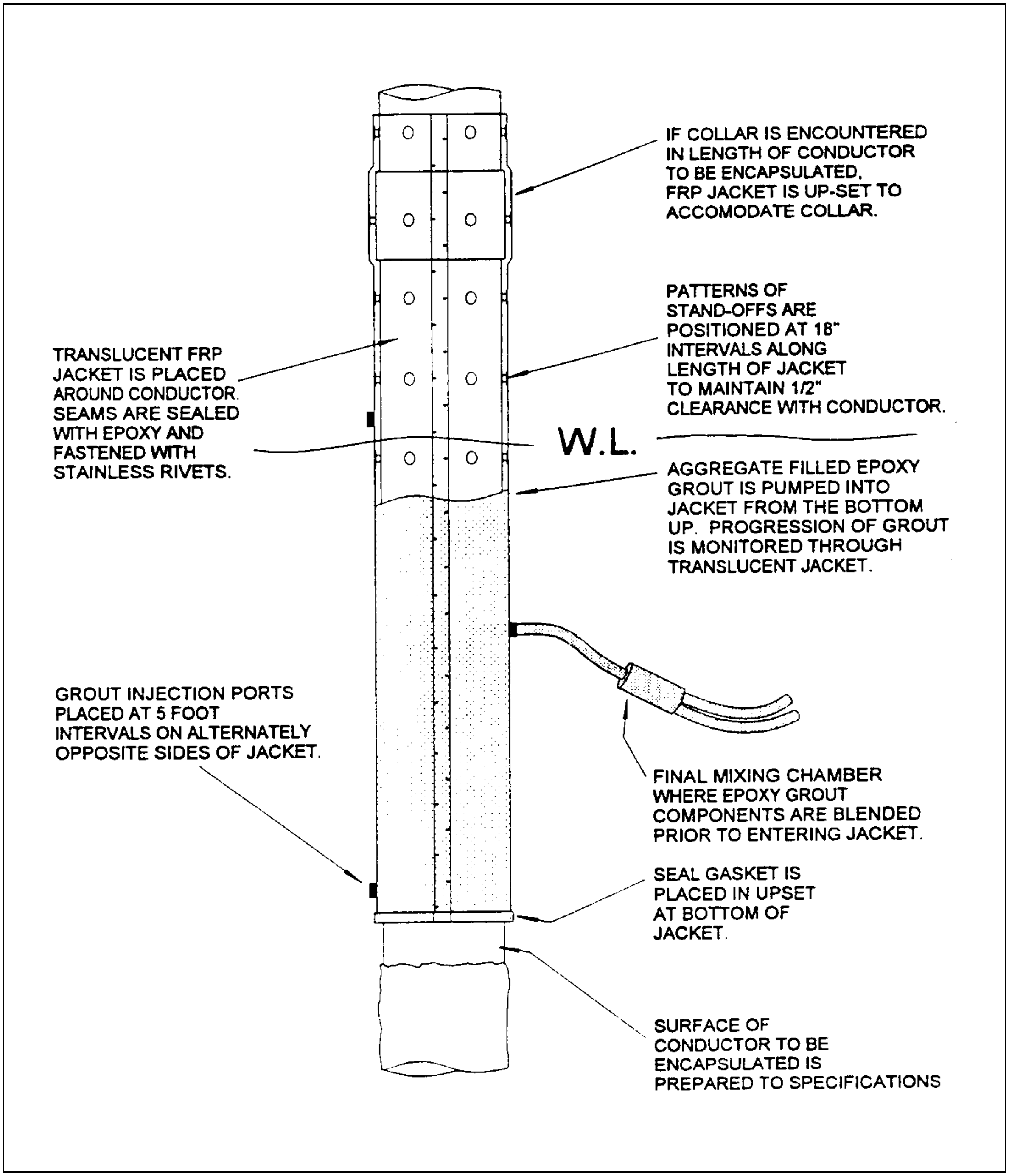

Figure 2.3 Typical View of a Translucent Jacket Filled with Mortar Epoxy Grout (Used by permission of Watson Bowman Acme Corp.)

The jackets are filled with an epoxy grout either below or above water. Snow (1996) discussed the features of the epoxy grout as follows:

1. It is free of inorganic accelerators such as chloride and other salts.
2. It has a similar appearance to concrete after curing.
3. It hardens free of bleeding.
4. It can be used with clean well-graded coarse aggregate to fill large voids.

2.8.1 Installation Procedure

The procedures described below do not include either surface preparation nor reinforcement repair or replacement. Tasks 1 to 4 described previously for the installation of CP jackets apply to the installation of a polymer encapsulation as follows:

1. Survey piles to determine elevation of the jackets according to design plans.
2. Clean pile surfaces within limits of new jackets of all unsound concrete, marine growth and other deleterious materials.
3. Sandblast or water blast exposed steel to a “near white” condition.
4. Repair or replace reinforcement as required.

Snow (1996) proposed two installation procedures. Both procedures 1 and 2 use epoxy grout between the jacket and the column. Procedure 1 refers to jackets that are installed above the mud line and procedure 2, to jackets that are installed below the mud line. Figures 2.4 and 2.5 show the general procedures followed during the installation of a translucent polymer grouted jacket.

In the first procedure, the jacket is placed above the mud line but below water, according to the installation procedure proposed by Snow (1996):

1. Position the jacket around pile at correct elevation, as indicated in the plans and seal longitudinal seams. The interior surface of the jacket has standoffs to keep a uniform clearance between the jacket and the concrete surface.
2. Affix bottom seal gasket with Hydrocote 3061, which is an epoxy paste adhesive for underwater construction.
3. Place temporary external bracing, banding or clamps around the jacket to keep it in place.
4. Allow seal epoxy to cure for four hours.
5. Attach grout umbilical to lower injection port.
6. Pump grout for 30 seconds.
7. Check for leaks.
8. Pump at least six inches of grout before moving to higher port.
9. Plug upper port and pump until grout reaches top of the jacket.

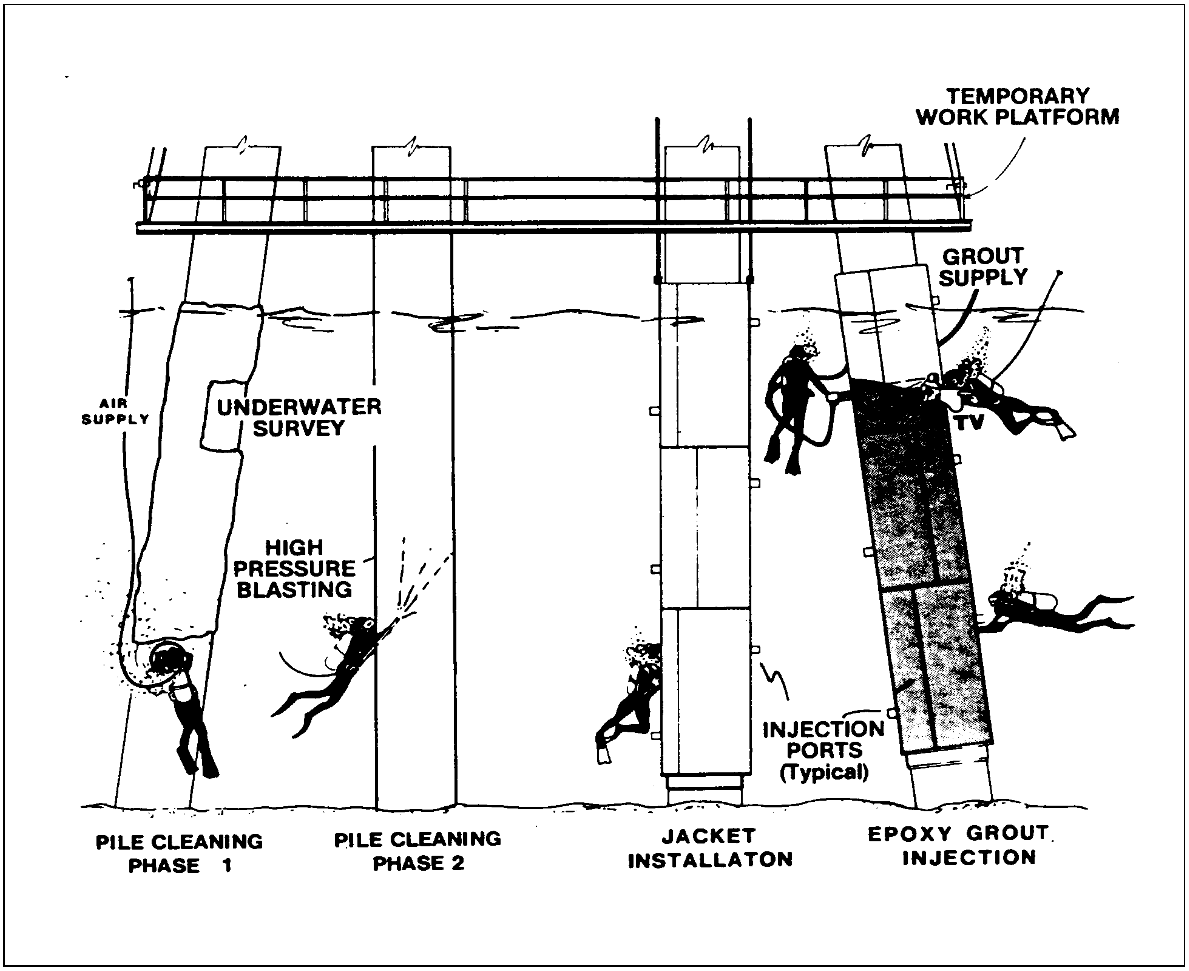

Figure 2.4 General Procedures During the Installation of a Translucent Epoxy Grouted Jacket
(Used by permission of Watson Bowman Acme Corp.)

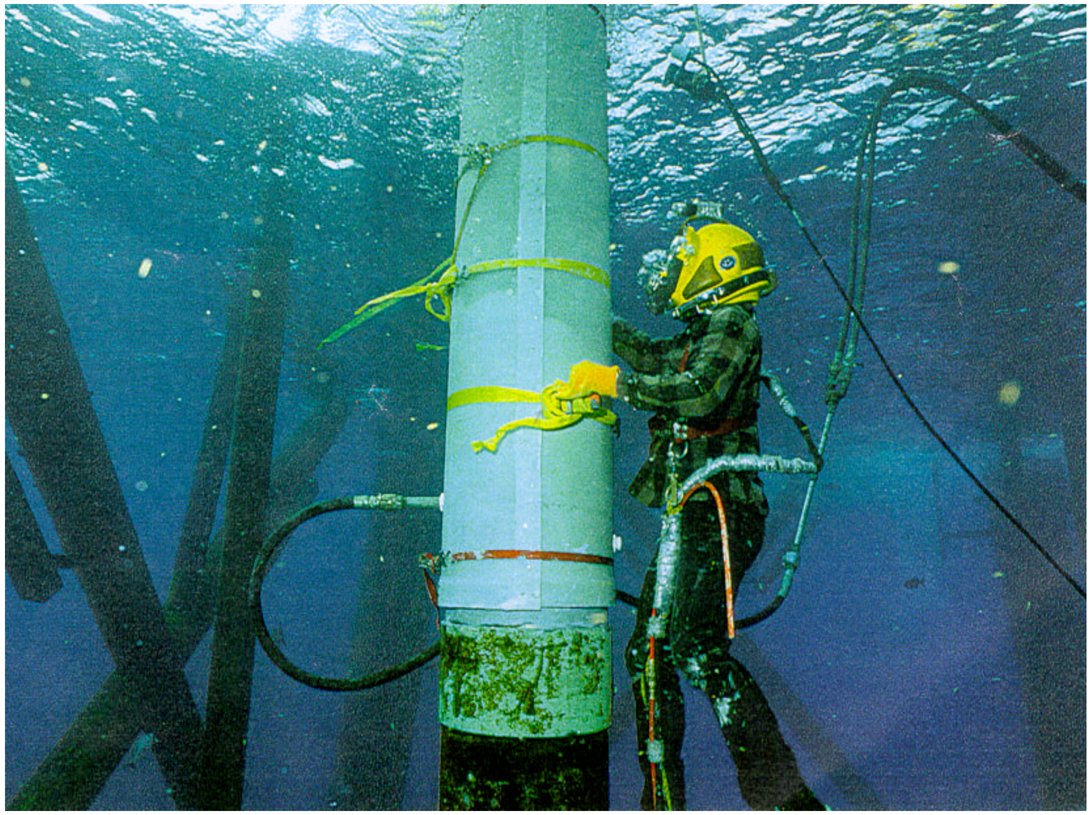

Figure 2.5 Underwater Encapsulation of a Translucent Epoxy Grouted Jacket
(Used by permission of Watson Bowman Acme Corp.)

In the second procedure, the bottom of the jacket is at an elevation below the mud line, according to the installation procedure proposed by Snow (1996)

1. Excavate a cavity around pile and below mud line to a depth of 2 feet below the bottom jacket elevation.
2. Fill scour cavity with grout.
3. Position jacket around pile and seal longitudinal seams.
4. Lower jacket into grout pool.
5. Place external bracing, banding or clamps around the jacket to keep it in place.
6. Allow grout in pool to cure for four hours.
7. Attach grout umbilical to lower injection port.
8. Pump grout for 30 seconds. Check for leaks.
9. Allow six inches of epoxy grout to cure for four hours before moving to a higher port.
10. Continue pumping until it reaches top of jacket.

2.9 <u>Hybrid Fiber Epoxy Composites</u>

Melligan (1997) reported repairs of piles using a hybrid fiber epoxy composite made up of either glass or carbon fiber reinforced wraps that are combined with epoxy matrices. Unlike the system described previously, the repair does not use a jacket; instead the repair method consists of composite wraps. The hybrid fiber epoxy composite system is applied below and above the water line and can cure in fresh water as well as in salt water.

Testing conducted by Neumer (1998) proved that concrete cylinders wrapped underwater and cured for 28 days both in fresh and salt water showed strength increases

32 percent to 55 percent higher than cylinders that were not wrapped due to concrete confinement. Neumer (1998) discussed that strengths increased 32 percent to 55 percent higher than the unwrapped ones. Unwrapped specimens had strength of 4.0 ksi. On the other hand, specimens wrapped in fresh water had a strength of 6.2 ksi, and specimens wrapped in saltwater had a strength of 5.3 ksi (Neumer 1998).

Pantazopolou (1996) reported the use of advanced composite materials to repair concrete specimens subjected to accelerate corrosion conditions in the laboratory. In this research, small size columns were studied. According to Pantazopolou (1996), the repair system consisted of:

1. A layer of dense low permeability grout overlaid on the damaged concrete.
2. A diffusion barrier to minimize penetration of moisture and alkali from grout.
3. Fiber composites wrapped around the repaired specimen to induce passive confining stresses to prevent future expansion of concrete due to corrosion of reinforcement.

The fiber composite material used was the Tyfo™ fiber wrap system composed of woven fabric containing glass fibers in the primary direction and orthogonal oriented aramid fibers (Pantazopolou 1996).

2.9.1 Installation Procedure

The installation procedure described below does not include reinforcement repair or replacement. If required, reinforcement can be repaired or replaced using guidelines described previously. The general procedure for the application of the hybrid fiber epoxy composite system is as follows (Melligan 1997):

1. Remove all algae and unsound concrete from the pile.
2. If cross section of pile is rectangular, sharp corners of rectangular section shall be rounded to a ¾ inch minimum radius.
3. Uneven surfaces shall be filled with thickened epoxy, grout or equal material.
4. Apply a primer layer of epoxy to all surfaces to receive the composite.
5. Mix epoxy and saturate the fiber.
6. Apply underwater composite (application should correspond with lowest possible tides).
7. Composite is applied using hand methods with a lap length at each vertical joint of at least 6 inches.
8. Horizontal gaps in excess of ½ inch are not permitted.
9. After composites have been applied, a final coat of epoxy is applied.
10. The final composite is then wrapped with a coat of polyethylene sheeting over all composite surfaces.
11. System requires approximately 30 days to cure completely.

2.10 <u>Cost Estimating</u>

Current methods of cost estimating at the pre-design stage are discussed in this section. Methods to estimate costs at the pre-design stage were considered “conceptual or preliminary” estimating. Four traditional methods of conceptual or preliminary estimating discussed were conceptual estimates, functional unit costs, system and parametric estimates. None of them were used in the development of the model. PACES, a knowledge based estimating system, was the only cost estimating method used as the point of departure for this research.

Cost estimates are classified based on accuracy. According to Ahuja (1994), the American Association of Cost Engineers classified cost estimating into order of magnitude, budget and definite estimates. Order of magnitude and budget estimates were also called conceptual estimates. Ahuja (1994) stated that order of magnitude estimate had accuracy between 30 percent to 50 percent and required zero percent to five percent design document completion. Budget estimates had accuracy between 15 percent to 30 percent and required five percent to 20 percent design document completion. Definite estimates had accuracy between five percent to 15 percent and required 60 percent design documents.

2.10.1 Conceptual Estimates

Gould (1997) stated that conceptual estimates were "typically developed by establishing a cost per usable unit from past engineers’ projects, and multiplying this cost by the number of units proposed". Gould's definition was based on a single parameter. An example of this type of estimate would be the repair cost per column, where one column was the usable unit described by Gould. According to Gould (1997), prices were usually adjusted using indices such as city cost index, size index and contingencies.

2.10.2 Functional Unit Cost Estimates

Functional unit cost estimates were similar to conceptual estimates. In this case, costs were calculated per square foot or linear foot. Examples of this type of estimate were the cost of repair per square foot of column area or the cost of repair per foot of column length. Typical costs per square foot or linear foot were based on historical data and were collected and updated continuously, such as those in The Assemblies Cost Book, published by RS Means (Gould 1997).

2.10.3 Assembly Estimates

In assembly estimates the cost was based on more detailed information such as square foot of jacket or volume of grout. Again, this cost was determined using historical data. The Ontario Ministry of Transportation (OMT) is using this approach (Thompson 1999). According to Thompson (1999), the OMT database contained tender cost prices, which allow using assembly estimates.

2.10.4 Parametric Estimating Based on Cost Estimating Relationships

Gregory (1992) discussed that traditional parametric cost estimating applied regression analysis and factor analysis to calculate cost parameters from historic data.

Foussier (2000) divided parametric cost estimating into specific models and universal models. According to Foussier (2000), specific models were based on the relationship between cost and parameters known as the Cost Estimating Relationships (CERs). Foussier (2000) stated that to create a specific model, the CER governing the model was defined using regression analysis. Linear regression analysis determined the equation for the line that was the best fit for a set of historical data by minimizing the square of the residuals between the data point and the value predicted by the straight line. CERs were intended to model the logic that defined the cost of similar products inherent to a specific company or industry (Foussier 2000).

Seel (2000) discussed an integrated system of information and techniques for estimating called INSITE. The system is a parametric cost estimating model developed by Prime Time for the United States Department of Energy (DoE) which was available via the Internet. According to Seel (2000), the model was comprised of CER and cost factors that could be adjusted or calibrated by the cost analyst to reflect the functions to be estimated. Seel (2000) stated that INSITE estimated costs were associated with the acquisition of buildings, site work, equipment, engineering and project management. The system could also be used to estimate operating costs for facilities (Seel 2000).

2.10.5 Knowledge Based Estimating Systems - PACES

According to Giarratano (1998), "knowledge–based system, expert system or knowledge-based expert system are often used synonymously". He discussed that an expert system could emulate "the decision-making ability of a human expert".

PACES was a knowledge based estimating system used to estimate construction costs for building facilities and site work and utilities (Talisman 1999).

According to Talisman (1999), PACES included 84 models for building facilities, and 36 models for site work and utilities. PACES also had the ability to estimate the construction cost of new simple span bridges. Talisman (1999) provided a brief description of PACES:

> "PACES contains cost models for many types of facilities. These models contain equation and algorithms based on engineering and construction experience. Each model contains a list of parameters, or variables that allow you to input specific information about the facility you want to create an estimate for. Each model has a set of required and secondary parameters. Required parameters are the minimum amount of information needed to create an estimate. Secondary parameters allow you to input any additional details known about the facility. PACES uses the model equations together with the parameter information to calculate an estimate of the construction cost of the facility."

The NSF provided funding for the research with the purpose of expanding the estimating capabilities of PACES to include bridge repair models. As stated by Gregory (1997) in the NSF proposal, one of the research tasks was:

> "To review and assess the existing, federally owned PACES bridge models. Specific engineering algorithms will be developed to augment the existing bridge models…"

2.11 Data Modeling

Kroenke (1997) discussed data modeling as "the process of creating a representation of the users' view of the data". He stated that data modeling was "the basis for all the subsequent work in the development of databases and their applications", and he proposed the entity relationship model as a data modeling tool. The entity relationship model was developed by Chen (1976). According to Kroenke (1997), an entity represented something that the user wanted to identify. Entities were composed of attributes, which described the entity's characteristics. Kroenke (1997) explained that each set of data or entity instance had a unique identifier, which was an attribute or a group of attributes called "key(s)". Entities were represented by rectangles and attributes were shown in ellipses and connected to the entity to which they belong.

Kroenke (1997) discussed that entities could be associated with one another in "relationships". He stated that the entity relationship model contained relationship classes and relationship instances.

> "Relationship classes are associations among entity classes, and relationship instances are associations among entity instances"

Kroenke (1997) proposed a methodology to test and validate entity-relationship models as follows:

> "Entity-relationship models should be evaluated. One technique is to list queries that could be answered using the data model. The design is then evaluated against these questions to ensure that the model can answer them."

An entity could be used later as the basis to populate a database by converting entities into tables. Kroenke (1997) explained that each row of a table contained an entity instance and the columns of the tables were the attributes.

2.12 <u>Data Analysis</u>

2.12.1 Normal Distribution

The statistical analysis theory discussed in this section focuses on techniques used to screen data in order to determine if the sample exhibited a normal distribution pattern and to identify outliers. Green (1999) recommended using histograms with superimposed normal curves and boxplots for this purpose.

In a histogram, the number of times a value occurred (frequency) was plotted, facilitating the identification of values, which departed markedly from other values in the sample (Green 1999). According to Hayslett (1968), if the data studied exhibited a normal distribution, the histogram followed the shape of a normal distribution. Spence (1968) stated:

> "The most obvious characteristic of the normal curve is its shape, somewhat like a bell, rising to a rounded peak in the middle and tampering off symmetrically at both tails."

Spence (1968) discussed that asymmetrical distributions that "tail off" in one direction were called "skewed". Green (1999) explained that a large positive value for skewness indicated a long right tail. A large negative value for skewness indicated a long left tail. Green (1999) defined "kurtosis" as a measurement of a sample peakedness that compared whether the peak of the sample was shorter or taller than that of a normal distribution. Green (1999) discussed that a large positive value for kurtosis indicated that the tail of the distribution of the sample was longer than that of a normal distribution. Conversely, a negative value for kurtosis indicated shorter tails. Green (1999) proposed to use the ratio of each statistic to its standard deviation to test the normality of the sample. He explained that normality could be rejected if such ratios were less than –2 or greater than +2.

The expected range of values in a normal distribution was defined in terms of the sample mean and the standard deviation. Spence (1968) discussed that in a normal distribution at least 95 percent of the values in the sample were expected to be greater than the mean minus two times the standard deviation and less than the mean plus two times the standard deviation.

According to Green (1999), the values of the mean and median of the sample could also be used to test the normality of the data; that is, the median and mean of a normal distribution were expected to be close values.

Another tool to study the distribution of a sample were the percentile ranks. Spence (1968) defined the percentile rank as “a value indicating the percent in a distribution falling at or below this score”. From Spence’s definition of percentile, the percentile marked the position of a data point within the sample. As an example, if a value was the 20th percentile then 20 percent of the values in the sample were below that number and 80 percent of the samples were above that value. Spence (1968) discussed that “quartiles” were the most common points used in the percentile scale. According to Spence (1968) the first quartile (Q_1) was the 25th percentile, the second quartile (Q_2) was the 50th percentile and the third quartile (Q_3) was the 75th percentile. Spence (1968) stated that the second quartile was also called the median. The author used two statistical software programs (Minitab® release 12 and SPSS version 9.0) that implemented the percentile ranks concept into a graph called a boxplot or box-and-whisker plot shown in Figure 2.6. Such a graph was composed of a box with two edges at each extreme called “whiskers” or “hinges”. The line within the box represented the 50^{th} percentile or the median of the sample. The upper limit of the box represented the third quartile or 75th percentile (Q_3). The lower limit of the box represented the first quartile or 25th percentile (Q_1).

Green (1999) proposed the following values as the maximum and minimum values of the samples, which should not be considered outliers:

$$\text{Smallest Value} = Q_1 - 1.5(Q_3 - Q_1)$$

$$\text{Highest Value} = Q_3 + 1.5(Q_3 - Q_1)$$

Green (1999) defined outliers as values that were between 1.5 to 3 box-lengths ($Q_3 - Q_1$) from either the first quartile or the third quartile. Green (1999) also discussed that values above 3 box-lengths from the third quartile or below the first quartile were called extreme values. Both statistical software programs Minitab® release 12 and SPSS version 9.0 used the above criteria to define the highest value, smallest value, outliers and extreme values. In the boxplots shown in SPSS version 9.0, the upper whisker and lower whisker of the box represented the highest and smallest values. Outliers were represented with an open circle. Extreme values were marked with an asterisk (*).

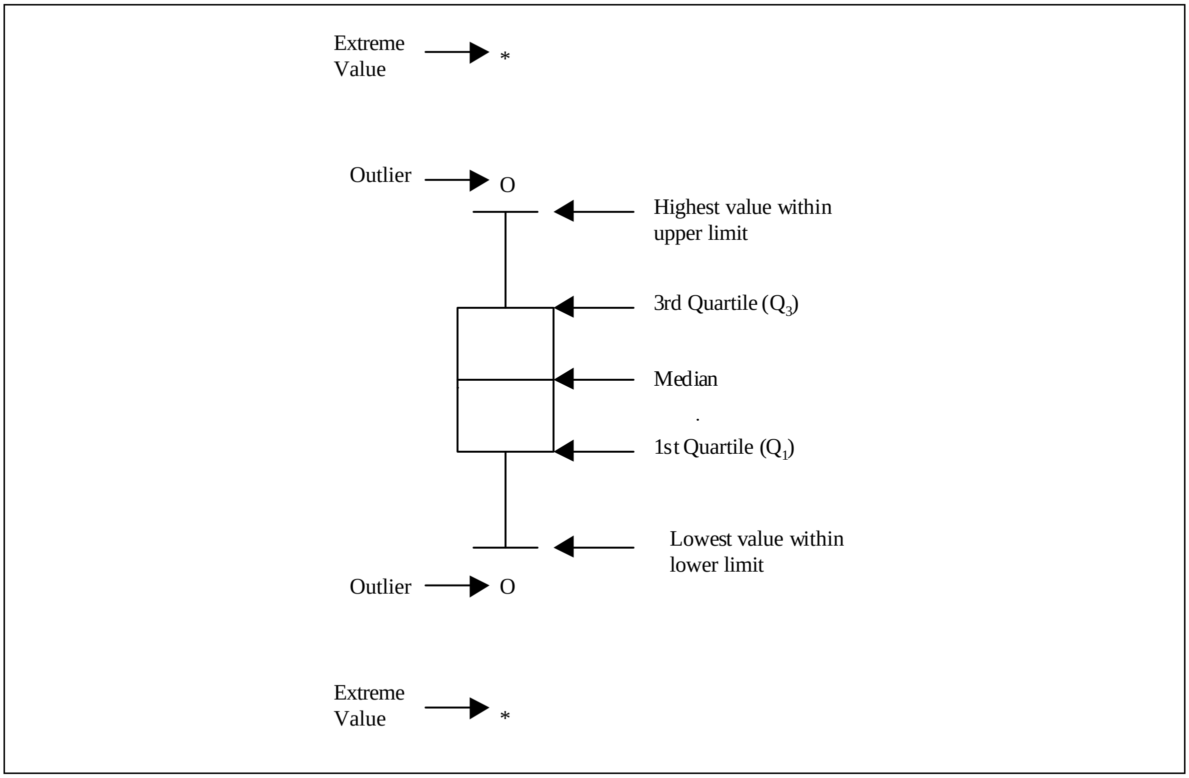

Figure 2.6 Typical Boxplot Components
(Used by permission of MINITAB INC.)

2.12.2 Empirical Probability

The probabilities used in this research were “empirical” probabilities, which were different than “classical” probabilities. Both probabilities applied to simple, mutually exclusive events. Below is a comparison of empirical and classical probabilities as discussed in the literature.

Hayslett (1968) defined simple events as events that were mutually exclusive and equally likely to occur. Events mutually exclusive could not occur at the same time. Assuming that such an event was called event A, Hayslett (1968) defined the probability of event A as the number of possible outcomes favorable to A divided by the total number of outcomes. Hayslett’s definition was the classical definition of probability.

According to Ingram (1974), the classical definition was "quite limited. In most real situations all possible outcomes do not have equal chances". As an example, Ingram (1974) discussed that based on the classical definition of probability the probability that a baby was either a boy or a girl was ½. However, Ingram (1974) provided birth rate statistics from the United States to show that the number of baby boys born was not the same as the number of baby girls. Ingram (1974) concluded that "some "obvious" probabilities, based on classical definition", were wrong. He proposed to use an "empirical" (relative frequency) definition of probability. The empirical probability was defined as the frequency of occurrence of event A divided by total number of events (Ingram 1974).

2.12.3 Tree Diagrams

Hayslett (1968) described a "tree diagram" used to calculate the probability of combinations of simple events. The tree diagram was composed of large branches and smaller branches sprouting from each one of the larger branches. According to Hayslett (1968), each large branch of the tree represented the probabilities of the possible outcome for the first event. Each smaller branch represented the probability of the possible outcomes for the second event. The probabilities of all possible combinations of the first and second event were calculated by multiplying the probabilities of the branches that were connected. Diekman (1998) discussed using tree diagrams to calculate cost associated with probabilities.

2.12.4 Neural Networks

The Ward Systems Group (2000) reported that neural networks were useful to analyze the data when a relation between the variables was suspected, but such relation could not be defined by simple inspection (Ward Systems Group 2001). The neural network classified data based on patterns learned from historical data. Such network produced an output, which listed the probabilities of each input set belonging to each of several categories (Ward Systems Group 2001). A set of data was classified into the category that had the higher probability (Ward Systems Group 2001). According to Giarratano (1998), neural networks were based on the weights associated with each one of its elements. The Ward Systems Group (2001) stated that a neural network:

> "….finds a relative importance value for each of the inputs. By figuring out a weighting scheme that signifies which inputs are more important to predicting the output, the net is more precise in making its classifications."

Giarratano (1998) stated that:

> "The programmer "programs" the net simply by supplying the input and corresponding output data. The net learns by automatically adjusting weights in the network that connects the neurons."

2.13 <u>Conclusions</u>

The bridge inspection guidelines that are discussed in this chapter define the type of damage, as well as, the quantitative values that should be recorded in a detailed bridge inspection report. Such guidelines should be considered in the design of a relational database in which detailed inspection data could be stored. Pontis™ Condition State definitions provided a qualitative value of the damage but not a quantitative value which is required to estimate quantities. Pontis™ MR&R actions were generic and did not provide specific construction tasks.

Repair technology refers to concrete and reinforcement repair guidelines, repair system technology included in the scope of this research, and design plans provided by FDOT. These guidelines should be considered when determining the construction task and the construction process that is required to repair a concrete pile.

Statistical and neural network principles discussed herein were considered when analyzing the data presented in the following chapters.

CHAPTER III

METHODOLOGY

3.1 Introduction

The methodology used in the research was closely related to the process used by an engineer to estimate material, labor, and equipment (MLE) quantities for a bridge repair project. In such a process an engineer should define the damage existing in the bridge, select construction tasks to repair such damage and estimate quantities. Thus, the estimating model was composed of a Damage Assessment Model, a Construction Process Model and a Parametric Quantity Model.

The estimating model developed was an expert system used to generate MLE quantities. Then, current cost data were applied to get a cost estimate for the repair project. The main advantage was that it was possible to estimate MLE quantities at the pre-design stage. Also, the new methodology allowed to estimate MLE quantities for repair projects for which there might not be historical data. With the exception of PACES, existing estimating methods, discussed in Chapter II, required complete construction documents to define accurate material, equipment and labor quantities and were based solely on historical data.

Figure 3.1 summarizes the deficiencies noted in current methodology, the proposed solutions and the methodology used in the research. This Chapter provides a discussion of the issues presented in Figure 3.1.

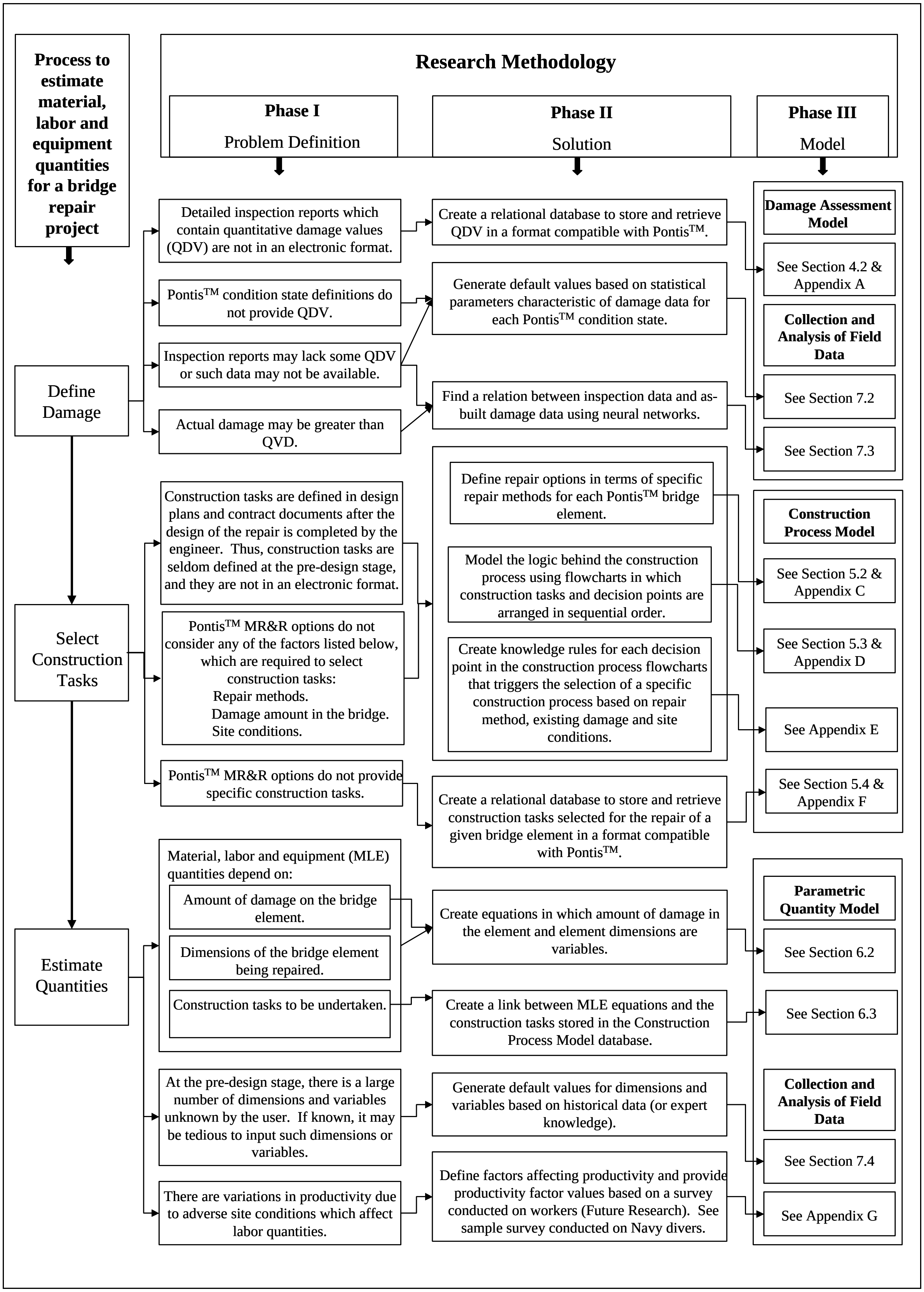

Figure 3.1 Research Methodology

3.2 Research Phases

For each one of the models the research was divided into three phases, as shown in Figure 3.1. In Phase I, emphasis was given to defining the problem to be solved. During Phase II, a solution was proposed, and in Phase III, a design was developed based on the proposed solution.

In Phase I, the research point of departure and the needs and trends in industry were determined. The purpose was to define what knowledge already existed in the research areas that could be applied for the development of the model, so that the models would incorporate repair technology currently used in industry. The gap between the deficiencies of the existing knowledge and the requirements of estimating MLE quantities for a bridge repair project defined the research problem in terms of each of the models that needed to be developed. In Phase II, a solution of the problems defined in Phase I was proposed by determining which tasks needed to be done in order to overcome deficiencies in the existing knowledge. In Phase III, the Damage Assessment Model, the Construction Process Model and the Parametric Quantity Model were developed based on the outcome of Phase I and II. Below, there is discussion of the research phases in terms of the Damage Assessment Model, the Construction Process Model and the Parametric Quantity Model.

3.2.1 Damage Assessment Model

In Phase I, research indicated that state DOTs maintained bridge inventory information on their Pontis™ databases. Therefore, a survey to collect existing databases was conducted. States that provided actual copies of their Pontis™ databases were

Connecticut, California, Mississippi, New Hampshire, South Carolina and Virginia. These databases were analyzed to define existing data. Analysis of Pontis™ data showed that a bridge inspector assigned a condition state to bridge elements after completing a detailed bridge inspection. Detailed bridge inspection data contained quantitative damage data, but Pontis™ qualitative definitions of condition state did not allow including such values. See Table 2.2 and 2.3. Nevertheless, other Pontis™ bridge data used to divide the bridge into elements and to define the span of the bridge in which the element was located were useful, readily available and in an electronic format in 38 state DOTs. This latter fact might facilitate the implementation of the model later; thus, it triggered the researcher's decision to use Pontis™ data.

Supported by the NSF and the Georgia Institute of Technology, the researcher attended a two-week seminar by FHWA on bridge inspection reports with the purpose of understanding current bridge inspection practices and data. Analysis of detailed inspection reports, inspection guidelines and as-built reports provided by the FDOT Corrosion Laboratory at Gainesville showed that indeed such data would be useful to determine existing damage in the bridge using quantitative terms, but such data were not in an electronic format. In some cases, the inspection reports were incomplete, and as-built reports showed that the actual damage was greater than the damage described in the inspection reports. Unlike new construction, due to the large number of elements and the advanced degree of deterioration existing at the time of the repair, repair projects required a large number of input parameters in the form of damage data. However, it was not feasible to expect the user to input such data each time an estimate was created.

To overcome such problems, a solution was proposed in Phase II, to create a relational database that could be used to store and retrieve data in a format compatible with Pontis™. The Damage Assessment Model, developed in Phase III, provided the structure of such a relational database, which was tested and validated by the user by developing a sample database.

In addition, default values were generated based on statistical parameters characteristic of damage data for each Pontis™ condition state. Using neural networks, a relation was found between actual damage and damage described in inspection reports. The methodology used in the statistical analysis is described later.

3.2.2 Construction Process Model

Attempts to model the construction process model that are described in the literature have focused on identifying the main stages of the construction process and describing the interaction between the different parts involved in the project. Sanvido (1994) identified the following five stages within the design of a facility:(1) acquire design project/work, (2) plan and control design, (3) acquire resources and services, (4) perform design, and (5) communicate design to others. Sanvido (1994) defined the components of each stage and the flow of information between the stages.

Vanegas (1987) modeled the interaction between owner, designer, and constructor. Such models provide an auditing framework to assure that all project activities are considered within the project plan and that each player in the project team is fulfilling his or her responsibilities.

The methodology presented in this section adds to the existing body of knowledge by focusing on the design phase of the project described by Sanvido (1994) and by modeling the thinking process used by the designer, one of the main project players identified by Vanegas (1987).

Phase I focused on developing the basic concepts, parameters and attributes of the knowledge-based assessment methodology. Most emphasis was given to understanding the construction processes of repair methods used in bridge repair and identifying the needs and trends in industry.

The knowledge acquired during Phase I was in the form of specifications, design drawings, design guidelines, expert knowledge and actual field data. Contractors, engineers and researchers who were active in the field of bridge repair provided the researcher with valuable expert knowledge. This knowledge was the product of years of experience, and it included heuristics or "rules of thumb". Five companies related to repair of bridge columns were contacted. These companies were Corrpro, Altrista, Master Builders, Fyfe and Mechanical City. These companies supported this research by providing a complete description of each of their products. In addition to surveys, eight field trips were organized during a two-month period with the collaboration of Corrpro, a firm specializing in CP jackets on bridge piles. The purpose of the trips was to understand the construction process of a repair project on Bridges 700076 and 700142. The bridges were located on State Route 404 over the Indian River Relief, in Brevard County, Florida. Detailed field data were collected during the installation of an integral pile jacket CP system.

The knowledge acquisition techniques used to collect information from the experts during interviews were informal reporting and protocol analysis. Informal reporting consisted of meetings with the experts where the expert explained the repair design and installation procedures. The experts also provided sample design for specific examples. The process of providing expert knowledge through specific examples is known as protocol analysis (www.rci.rutgers.edu).

One of the challenges recognized during Phase I was the large number of repair options available due to the large number of bridge elements. Analysis of Pontis™ maintenance, repair and rehabilitation (MR&R) actions showed that Pontis™ did not define either the repair method or specific construction tasks. As a solution, in Phase II, the researcher proposed to define repair method options for each one of the Pontis™ bridge elements to grasp the real scope of the problem. The methodology used for the elements and repair options outside the scope of the research would be the same.

The main problem defined during Phase I, not unique to bridge repair, but rather common in most construction projects, was that the logic used to define the construction process and construction tasks existed in the mind of the engineer, but it was not explicitly defined until 100 percent design documents were complete. The solution to such a problem was to model the logic behind the construction process of bridge repair by combining repair practices, repair guidelines and design codes.

A third challenge, unique to bridge repair, was the fact that construction tasks might be repeated several times within the same project due to the large number of bridge elements showing similar components, dimensions and site conditions. Conversely, damage parameters might have different values among similar bridge elements of the same repair project, triggering the selection of different construction tasks. As a result, within an estimate, there would be a large number of construction tasks for each one of the bridge elements and those tasks might or might not be the same for all bridge elements. The solution proposed during Phase II, was to define construction task using a relational database compatible with the damage assessment and linked to the construction process logic, so that once construction tasks were selected for a given element by the Construction Process Model, they could be stored and retrieved in the relational database.

In Phase III, a Construction Process Model was developed which consisted of seven repair matrices that related repair options to each Pontis™ element. In addition, the model included construction processes flowcharts that modeled the logic behind a repair project and a relational database. The flowcharts combined construction tasks and decision points to define the construction sequence. Knowledge rules for each decision point that triggered the selection of the construction tasks were also defined in terms of input parameters, damage existing in the bridge and site specific condition. The construction process relational database was tested and validated by the user by developing a sample database. To validate the Construction Process Model flowcharts, construction activities required in 14 FDOT construction projects, which involved the repair of 1,259 bridge piles, were compared to activities predicted by the flowcharts. The findings showed that the flowcharts included all activities described in the project plans. Table 3.1 lists FDOT projects used to validate the flowchart.

Table 3.1 FDOT Projects and Bridges Used to Validate the Construction Process Flowcharts

Bridge ID	Project Number	Bridge Name	Number of Piles	Facility Carried
720076	SPN 72040-3570	Mathews	195	S.R. 10A
700008	FPN 237732-1-52-01	Eau Gallie	72	S.R. 5
700069	SPN 70100-3527	Banana River	105	S.R. 520
720057	SPN 72250-3552	Dunn Creek	128	S.R. 105
770352	SPN 72250-3552	Moncrief Creek	121	S.R. 111
460072	SPN 46010-3506	Phillips Inlet	49	U.S. 98
490032	FPN 405942-1-52-01	Apalachicola	311	U.S. 98
700006	SPN 70000-3502	Crane Creek	46	S.R. 5
700025	SPN 70070-3506	Sykes Creek WB	4	S.R. 528
700112	SPN 70070-3506	Sykes Creek EB	4	S.R. 528
790086	SPN 79010-3506	Turnbull Creek	82	S.R. 5
720063	SPN 72260-3540	Haulover Creek	42	S.R. 105
720044	SPN 72100-3576	San Pablo River	11	S.R. 10A
720056	SPN 72250-3561	San John River	53	S.R. 105

3.2.3 Parametric Quantity Model

Talisman Partners, as a partner of this NSF sponsored research, provided general information on PACES, a federally owned software used to estimate construction costs, which also contained models for construction of new simple span bridges. The main problem defined in Phase I, was that PACES did not include models for repair projects. Problems unique to repair of bridge elements, discussed previously, could not be addressed using the existing PACES methodology because of the large number of input parameters that were required due to the damage existing in the bridge and the large number of bridge elements. In PACES methodology, most of the input parameters were constant within the same project, minimizing the amount of input parameters. As an example, considering the construction of a new bridge, the dimensions of the piles most likely will be constant throughout the bridge. Thus, few parameters were required to estimate bridge pile quantities. In the case of bridge repair, there might be hundreds of values for the input parameters required to define the damage in the bridge, which might result in the selection of different construction tasks for each one of the bridge piles.

In Phase II, a solution was proposed to develop equations to estimate MLE quantities similar to those used in PACES and to link them to the Damage Assessment Model and the Construction Process Model. In Phase III, such parametric equations were developed and they were linked to the Construction Process Model and Damage Assessment Model using a relational database. The Parametric Quantity Model relational database was tested and validated by the user by developing a sample database. Sample parametric equations for an integral CP jacket were developed, and they were tested by applying them to estimate MLE for the FDOT Contract No. 404106-1-52-01.

A second problem defined during Phase I of the research, was that duration of construction tasks and factors affecting productivity were unknown for the construction tasks defined previously in the Construction Process Model. Construction data collected by the researcher while observing the repair of bridge pilings in Melbourne, Florida, referred to a single bridge; therefore, it might or might not be representative of other bridge projects. The solution proposed consisted of conducting a sample survey among Navy divers. The results of such a survey were analyzed and discussed in Appendix G.

The survey did not include all construction tasks, but it provided a methodology to collect data in future research.

The following tasks were involved in the development of the Parametric Quantity Model:

- Define MLE requirements for each construction task and subtask
- Create parametric equations to calculate repair quantities
- Define required parameters and secondary parameters
- Provide default values for secondary parameters
- Define the duration of each task
- Define factors that affect the duration of each task.

3.2.4 Data Modeling

The methodology included the design of the structure of a relational database for each one of the models developed. The tasks involved in data modeling include the following tasks:

- Define the functional requirements of the data
- Organize the data in entities and tables
- Establish the relationship between the entities
- Identify data existing in the Pontis™ database
- Provide sample data from inspection reports
- Create a sample database
- Develop sample queries to illustrate the use of the data and to validate the relational database structure

Full development of the relational database and the integration with Pontis™ are recommended for future research

3.2.5 Statistical Analysis

The statistical analysis focused on screening the data to identify outliers and to determine if the sample exhibited a normal distribution pattern. This task was done using (1) histograms with superimposed normal curves and (2) boxplots.

The following statistical descriptors of the data were used to determine if the distribution was not normal:

- The ratio of skewness and kurtosis to its respective standard were less than -2 or greater than +2.
- The values of the mean and median of the sample did not show close values.
- Ninety-five percent of the values in the sample were not in a range defined between the mean minus two times the standard deviation and the mean plus two times the standard deviation.

Once the assumption of normality was confirmed, it was possible to use statistical descriptors such as the mean and the standard deviation as default values for the Damage Assessment Model.

3.3 Conclusions

The methodology presented in this chapter is intended to capture the decision-making process used by an engineer to estimate material, labor, and equipment (MLE) quantities for a bridge repair project. In such a process, an engineer should define the existing damage in the bridge element, select construction tasks to repair such damage, and estimate quantities.

To define the damage, an engineer should identify a data source that provides quantitative information about the existing damage in the element that is being repaired and then identify the deficiencies of these data. In the case analyzed in this research, detailed bridge inspection reports were identified as the best data source to define the amount of existing damage in a concrete bridge pile. Since actual damage in the element may be larger than the damage described by detailed inspection report (a deficiency of the data), the engineer may increase the amount of damage that is considered. It was not clear how an engineer would guess a value to increase the amount of damage given by the inspection report. In the methodology, such a “guessing” process was captured using neural network and statistical analyses of both detailed inspection data and as-built quantities.

To select construction tasks that are required to repair an element, an engineer should follow and meet the criteria that are set by existing specifications and construction repair guidelines. As an example, ACI 546.1R (1980) provides guidelines on concrete repair and recommends removing all unsound concrete while repairing a concrete element. Therefore, when designing the repair of concrete bridge piles, the engineer should ask himself “is there unsound concrete?” In the methodology, when modeling the construction process logic of repairing concrete, such a question became a decision point within the construction process flowchart for concrete repair. Then, a decision rule for such a decision point was defined based on available data at the pre-design stage. In this case, inspection data could be used to determine whether or not there was unsound concrete in the pile. Construction tasks that were involved in removing unsound concrete were arranged in sequential order following the decision point described above. Construction tasks could then be selected based on the output of the decision point.

Similarly to estimate quantities, the engineer most likely would look at the design plans to recall what construction activities are required for each element. Then, the engineer would prepare a detailed quantity take off based on the unique dimensions of the element that is being considered and the existing damage. In the methodology, storing selected construction tasks in a relational database and retrieving them later to estimate quantities imitated the process of “recalling construction activities”. The quantity-take off process could be replaced by pre-defined MLE equations that were linked to the construction tasks in which the dimensions of the element that was being repaired and the existing damage were variables that could be defined at the pre-design stage.

CHAPTER IV

DAMAGE ASSESMENT MODEL

4.1 Introduction

This chapter provides a methodology to collect and maintain detailed inspection data in an electronic format. Specific research objectives accomplished in this chapter are: (1) prove that detailed inspection data could be stored in a database that was compatible with the existing Pontis™ database maintained by state departments of transportation; (2) define the amount and type of damage existing in a bridge using quantitative damage values; and (3) expand the Pontis™ Condition State definitions by describing the damage on the element using specific and quantitative terms. These objectives are related to the research methodology section highlighted in Figure 4.1

Detailed bridge inspection data were modeled using the entity-relationship model so that the damage existing in a bridge could be defined using quantitative terms. These data were required to estimate repair quantities and to define the construction processes. These data were not stored in the current Pontis™ database. The Pontis™ condition state definitions provided only a generic description of damage but they did not quantify the damage with specific values. To make the model compatible with the existing Pontis™ database, the model used the same attributes that Pontis™ used to identify the bridge, to describe the element and to locate the element within the bridge. Table 4.1 defines the functional needs of the entities by discussing why such entities are needed.

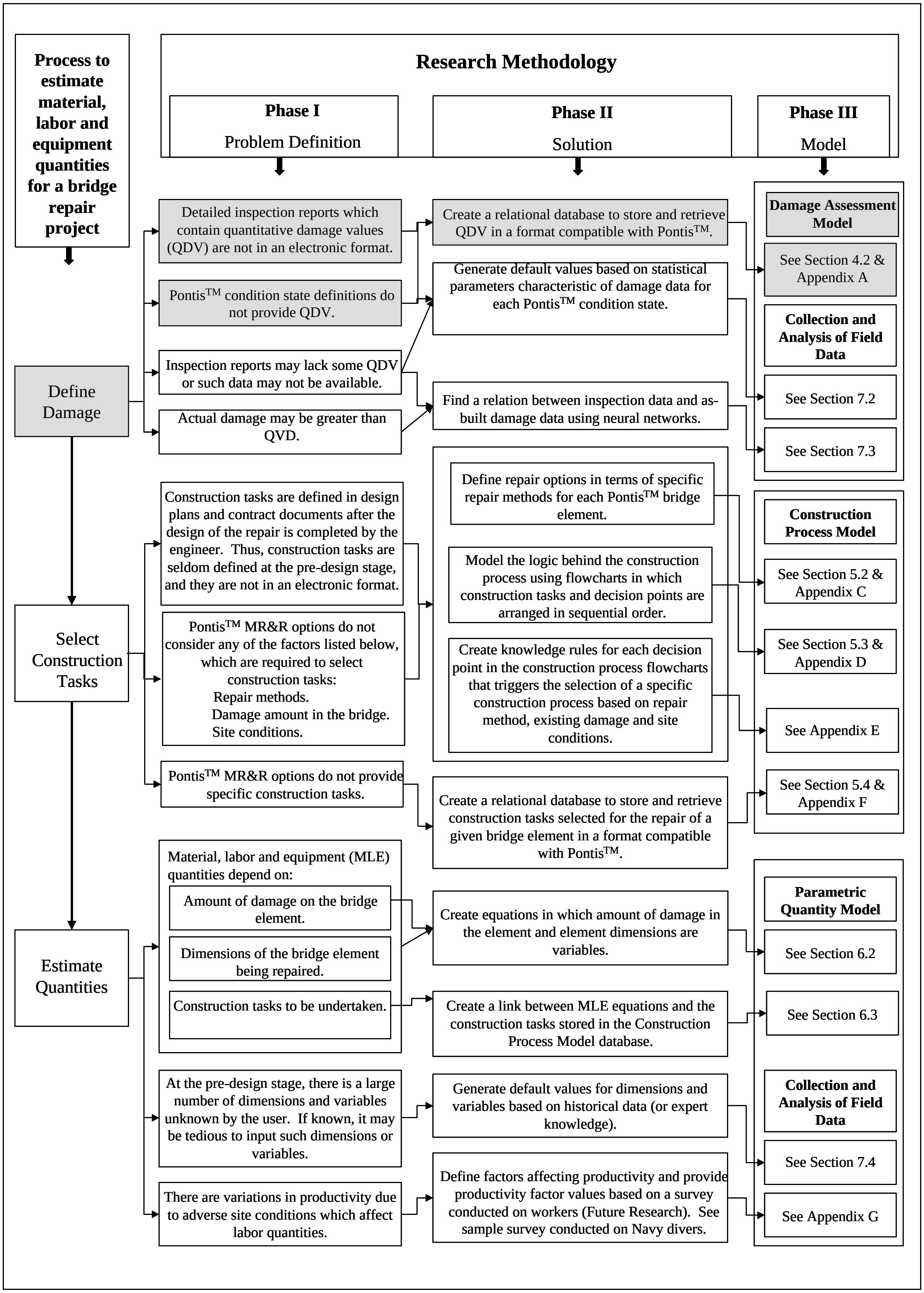

Figure 4.1 Research Methodology

Table 4.1 Functional Needs of Entities Used by the Construction Process Model

Goal	Entity	Discussion
Identify each element of a bridge and its Pontis™ condition state	"element"	To uniquely identify an element within a bridge, the model needed to know to which bridge the element belonged, the span of the bridge in which the element was located, the type of element and the element identification number. Once the element was identified, a Pontis™ condition state could be assigned to it.
Describe the type of element	"elementdef"	The model needed to know what type of element was being considered in order to select a repair procedure. The definition of each type of element was stored in the model, so that the user did not need to re-enter it or to store it in multiple places.
Divide elements in sections	"sectiondef"	Different repair methods, equipment and labor were required at different sections of the element based on the element geometry, structural behavior and the surrounding environment.
Describe the type of damage that may be present on a given type of element	"damagedef"	The model needed to know the type of damage to select the correct construction task. The description of the type of damage was stored in the model, so that the user did not need to re-enter it or to store it in multiple places.
Define the parameters required to describe a given type of damage	"parameterdef"	Each type of damage needed to be defined using quantitative parameters. The description of each parameter was stored in the model so that the user did not need to re-enter it or to store it in multiple places.
Quantify the damage existing on each element of a bridge	"damage"	To quantify the existing damage, the model needed to have a value for each damage parameter.

This chapter provides a description of the entities used to group the data, tables to illustrate sample data contained in the entities and results of queries used to retrieve data from the database. The data were modeled using entities, which were made up of attributes. An entity could be used as the basis to populate a relational database by converting entities into tables and attributes into columns of the table (Kroenke 1997). To illustrate the function of the entities and to validate the model, a sample relational database was created by the author using Microsoft ® Access 2000. The sample database tables and fields (fields were columns of the tables) had the same names as those used for the model's entities and attributes. Due to limitations on sizing field names in Microsoft ® Access 2000, short "software-like" names were used. Queries used to test the model are discussed in this chapter and presented in detail in Appendix B.

In all the figures describing entities used by the model, attributes shown in bold font could be retrieved from the Pontis™ database. All other attributes did not belong to the Pontis™ database and were unique to the Damage Assessment Model. The data stored in those attributes were not stored in the Pontis™ database either. Attributes shown underlined were "key" attributes used to identify each set of data. In all the sample data tables, data shown highlighted referred to an example pile used to illustrate the methodology. The example pile was pile number 6 located on span 6 of the Howard Frankland Bridge. All data presented in this chapter refer only to spans. One deficiency of Pontis™ was that for vertical elements, such as piles, Pontis™ data referred only to the span were the element was located, but Pontis™ did not specify the bent. Such a deficiency was not addressed in this research, and it is recommended as future research. The FDOT bridge number was 150107. The Pontis™ element used to classify the pile was

226. According to FDOT detailed bridge inspection report, the pile showed spall damage and reinforcement cross section loss and was classified in Pontis™ Condition State 4.

4.2 Damage Assessment Model Structure

4.2.1 The "Element" and "Elementdef" Entities

The "element" and "elementdef" entities are shown in Figure 4.2 and 4.3 respectively. The "element" entity was used to model the data required to identify each bridge and its respective elements.

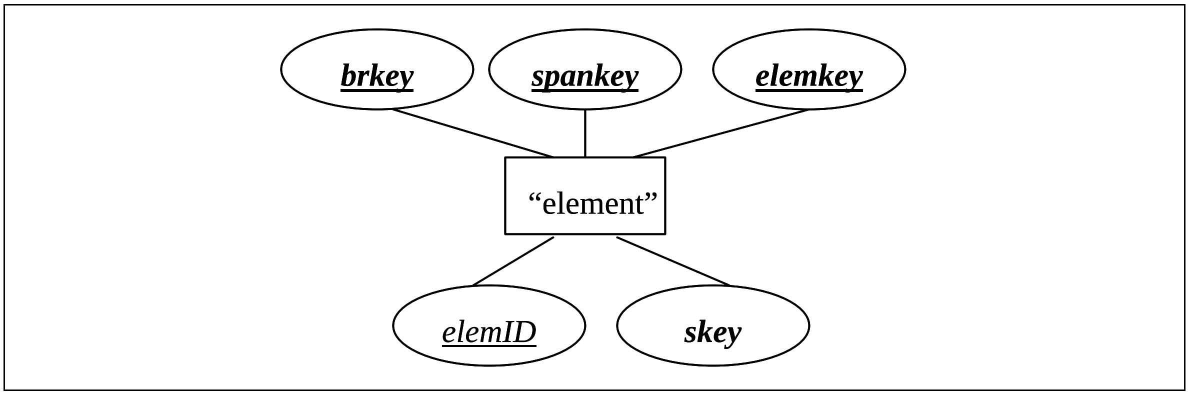

Figure 4.2 The "Element" Entity and its Attributes

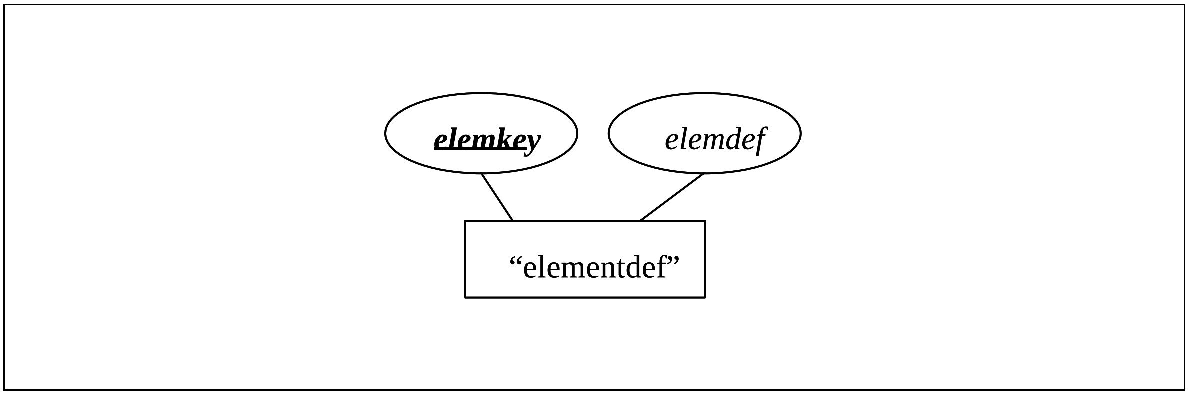

Figure 4.3 The "Elementdef" Entity and its Attributes

A description of the attributes on the “element” entity is given below.

- ***brkey*** **–** (Key attribute, Pontis™) - Bridge identification number.
- ***spankey*** **–** (Key attribute, Pontis™) - Bridge span where the element was located.
- ***elemkey*** **–** (Key attribute, Pontis™) - Element identification number as defined in the *Guide for Commonly Recognized (CoRe) Structural Elements* (ASSHTO 1997). The attribute *elemkey* defined a structural element of the bridge such as a prestressed concrete pile.
- *elemID* - (Key attribute) - Identification number of a specific element such as Pile # 6.
- ***stkey*** **–** (Pontis™) - Element condition state as defined in the *Guide for Commonly Recognized (CoRe) Structural Elements* (ASSHTO 1997). The author assigned a Pontis condition state to each element based on data from detailed inspection reports prepared by FDOT. Pontis™ data listed the number of elements in a given condition state, but it did not assign a condition state to a specific element.

The “elementdef” entity, shown in Figure 4.3 contained the following attributes:

- ***elemkey*** **–** (Key attribute, Pontis™) - Defined previously in the “element” entity.
- ***elemdef*** **–** (Pontis™) - Short description of the element.

Sample data contained in the entities “element” and “elementdef” are shown in Tables 4.2 and 4.3 respectively.

Table 4.2 Sample Data Contained in the "Element" Entity

brkey	***elemkey***	***spankey***	*elemID*	***stkey***
150107	226	6	6	4
150107	226	12	8	2
150107	226	13	3	4
150107	226	52	1	2
720076	227	46	1	2

Table 4.3 Sample Data Contained in the "Elementdef" Entity

elemkey	***elemdef***
204	Prestressed concrete pile extension
226	Prestressed concrete pile
205	Reinforced concrete pile extension
227	Reinforced concrete pile

4.2.2 The "Sectiondef" Entity

The "sectiondef" entity, shown in Figure 4.4, was modeled to allow the user to define the number of sections in which the element might be divided. Sample data contained in the "sectiondef" entity are shown in Tables 4.4. The "sectiondef" was composed of the following attributes:

- ***elemkey*** – (Key attribute, Pontis™) – Defined previously.
- *itype* – Took values "default" or "user" to define whether it was a default value or a user defined value.
- *i* – (Key attribute) - Numbered the section.
- *sectiondef* - Provided a short description of the section.

It was necessary to define sections in the elements because different types of repair methods, equipment or labor were required at specific sections due to the element's geometry, its structural behavior, and the surrounding environment. Considering a bridge pile, the location of damage with respect to the water level triggered the model to define the construction method, equipment, and crew required to repair the damage on the pile. As an example, if the damage on the pile was located above the water level, the pile could be repaired from a floating platform. The default values used to divide a bridge pile were based on the mean low water tide (MLW) as follows: (1) Above MLW, (2) Below MLW (in the range of 0 ft to -3 ft) and (3) Below MLW (-3 ft or more).

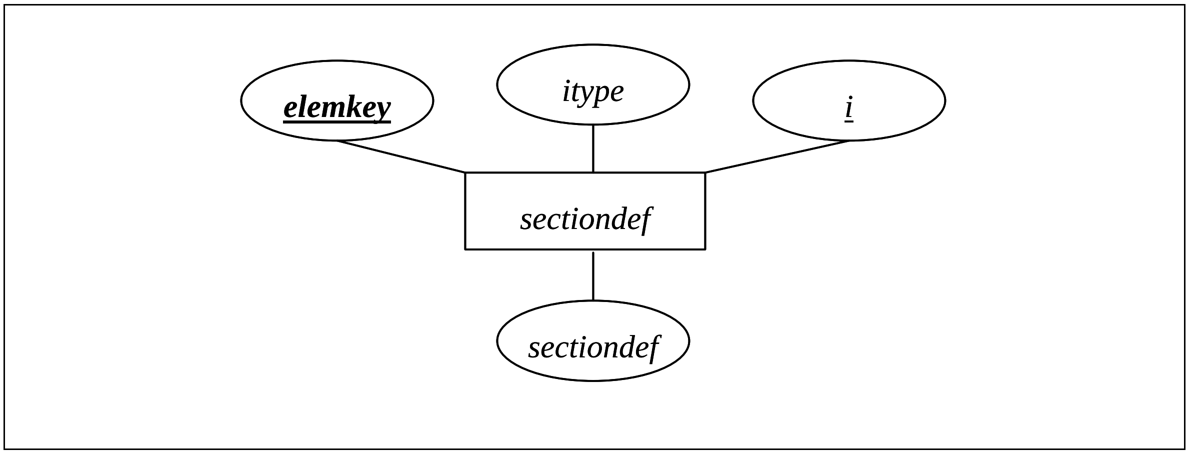

Figure 4.4. The "Sectiondef" Entity and its Attributes

Table 4.4 Sample Data Contained in the "Sectiondef" Entity

elemkey	*itype*	*i*	*sectiondef*
226	default	1	Above MLW
226	default	2	Below MLW (0 ft to -3 ft)
226	default	3	Below MLW (-3 ft or more)

4.2.3 The "Damagedef", "Parameterdef" and "Damage" Entities

The data required to define and describe the type of damage for each type of element were modeled in the system using the "damagedef"and "parameterdef" entities. The "damage" entity contained the values used to quantify the damage in the elements. The Pontis™ condition state definitions provided only a description of the damage but not a quantitative value of the damage. Therefore, it was necessary to expand the Pontis™ condition state definitions to model the damage on the element using specific and quantitative terms for each type of damage. From a repair perspective, the type and amount of damage might result in different construction tasks, which in turn might result in material, labor and equipment quantities variations within the same Pontis™ condition state. The "damagedef" entity, shown in Figure 4.5 (a), was composed of the following attributes:

- ***elemkey*** – (Key attribute, Pontis™) - Defined previously.
- *damID* – (Key attribute) – Number used to identify the type of damage for a given element.
- *damdef* – Provided a short description of the damage such as longitudinal reinforcement corrosion.

The "parameterdef" entity, shown in Figure 4.5 (b), was composed of the following attributes:

- ***elemkey*** - (Key attribute, Pontis™) – Defined previously.
- *damID* – (Key attribute) – Defined previously.
- *parameterID* – (Key attribute) - Identified the parameter used to describe the damage.

- *parameterdef* - Provided a short description of the parameter under consideration.

Sample values stored in the "Damagedef" and "Parameterdef" entities are shown in Tables 4.5 and 4.6 respectively.

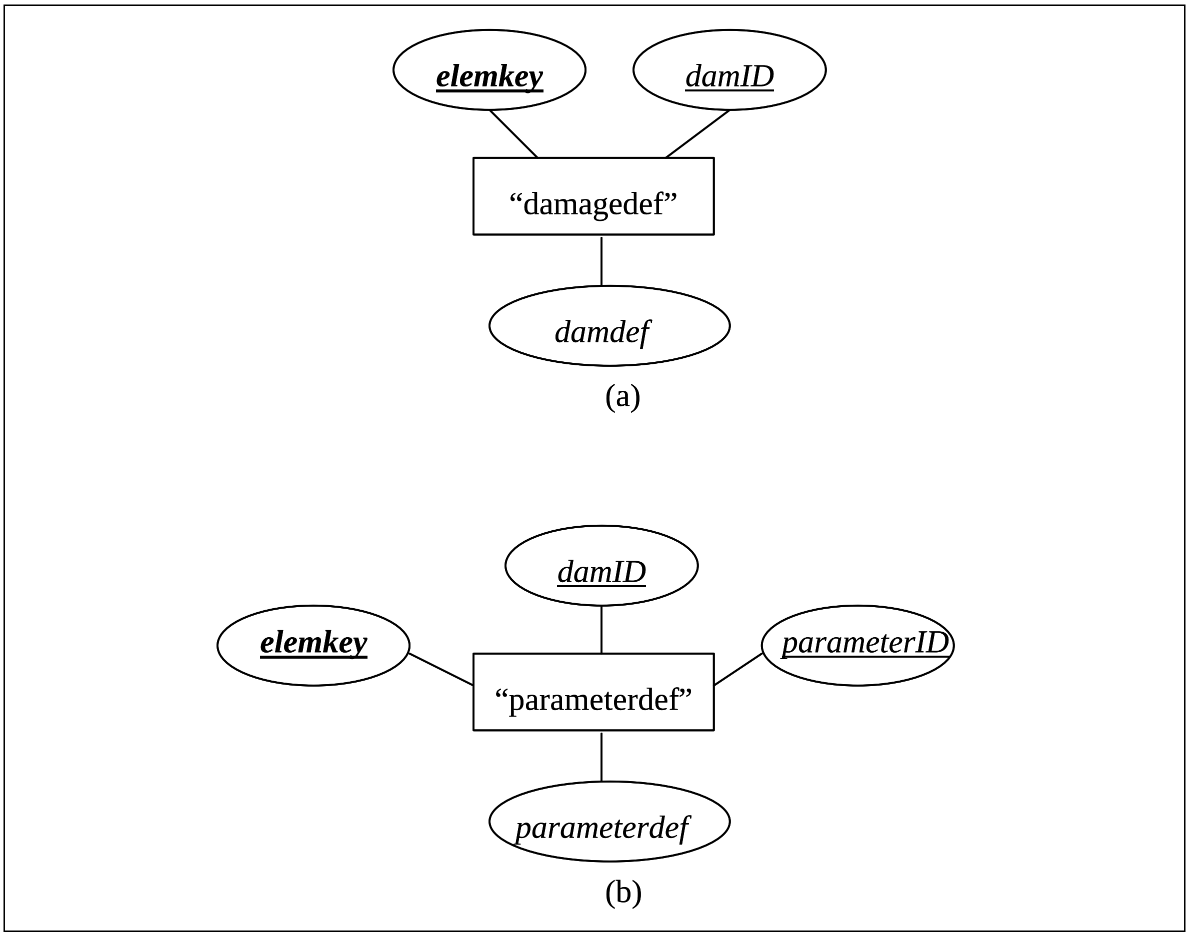

Figure 4.5 (a) The "Damagedef" Entity and its Attributes (b) The "Parameterdef" Entity and its Attributes

Table 4.5 Sample Values for the Attributes of the "Damagedef" Entity

elemkey	*damID*	*damdef*
226	1	Spall
226	2	Longitudinal reinforcement corrosion
226	3	Crack
226	4	Transverse reinforcement corrosion
226	5	Delamination

Table 4.6 Sample Values for the Attributes of the "Parameterdef" Entity

elemkey	*damID*	*parameterID*	*parameterdef*
226	1	1	Spall length
226	1	2	Spall depth
226	2	3	Spall width
226	2	1	Reinforcement cross section loss
226	2	2	Length of reinforcement missing
226	2	3	Length of unsupported steel
226	3	1	Crack class
226	3	2	Crack length
226	5	1	Delamination length
226	5	2	Delamination width

After defining the type of damage with specific terms, the amount of damage in the element was modeled using the “damage” entity, shown in Figure 4.6. This entity was made up of the following attributes:

- ***brkey*** – (Key attribute, Pontis™) – Defined previously.
- ***spankey*** – (Key attribute, Pontis™) – Defined the bridge span in which the element was located.
- ***elemkey*** – (Key attribute, Pontis™) – Defined previously.
- *elemID* – (Key attribute) – Defined previously.
- *damageloc* – (Key attribute) – Defined the location of the damage within the element.
- *damID* – (Key attribute) – Defined previously.
- *parameterID* – (Key attribute) – Defined previously.
- *i* – (Key attribute) – Defined previously.
- *itype* – Defined whether the value “ï” was a default value or a user defined value.
- *value* - Stored a value that quantified the damage observed.
- *unit* – Stored the corresponding unit for the quantity stored in the attribute value. Sample values stored in the “damage” entity are shown in Table 4.7.

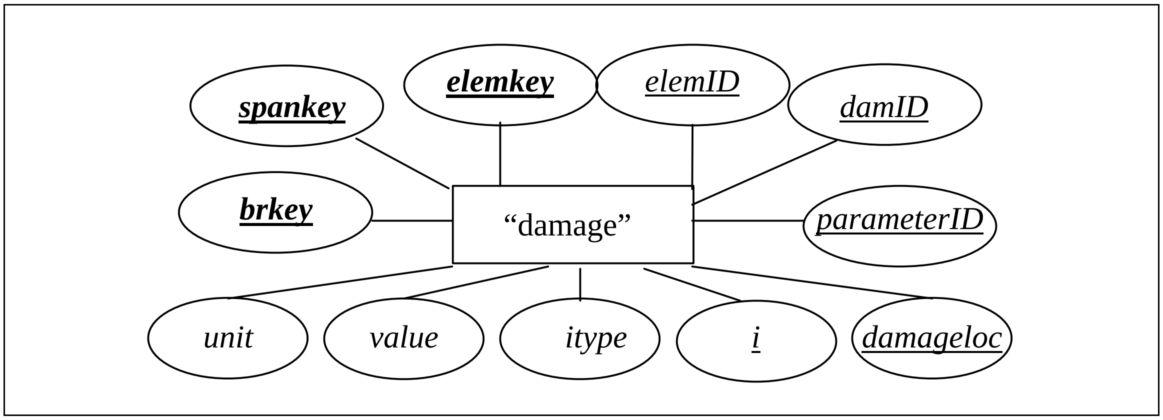

Figure 4.6 The “Damage” Entity and its Attributes

Table 4.7 Sample Values for the Attributes of the “Damage” Entity

brkey	***elemkey***	***spankey***	*elemID*	*damageloc*	*damID*	*parameterID*	*i*	*itype*	*value*	*unit*
150107	226	6	6	E	1	1	1	default	39	inch
150107	226	6	6	E	1	2	1	default	4	inch
150107	226	6	6	E	1	3	1	default	20	inch
150107	226	6	6	E	2	1	1	default	100	percent
150107	226	12	8	SE	1	1	2	default	16	inch
150107	226	12	8	SE	1	2	2	default	1	inch
150107	226	12	8	SE	1	3	2	default	6	inch
150107	226	13	3	E	1	1	3	default	43	inch
150107	226	13	3	E	1	2	3	default	3	inch
150107	226	13	3	E	1	3	3	default	16	inch
150107	226	13	3	E	2	1	3	default	100	percent
150107	226	52	1	NW	3	1	1	default	2	class
150107	226	52	1	NW	3	2	1	default	47	inch

4.3 Example Queries

To illustrate the type of data that could be stored and retrieved from the damage assessment model, three example queries were developed by the author. The first query retrieved all detailed inspection data stored in the database for a bridge specified by the user. The second query retrieved the amount of damage for a given type of damage and for a single element specified by the user on a given bridge. The third query retrieved spall data for a concrete pile on a given bridge and calculated a volume from the spall dimensions. The data retrieved by the queries, were modeled using the “damage”, “sectiondef”, “damagedef”, “parameterdef” and “elementdef” entities, and they were the same sample data shown in Tables 4.2 through 4.8.

Example 4.1. Report of Existing Damage on a Bridge

The purpose of this example was to generate a report that described all damage data stored in the model for a given bridge. Such a report provided the engineer with a general overview of the bridge condition. The report, shown in Figure 4.7, listed several types of damage for different elements. Such data were retrieved from the model, using a structured query language (SQL) code, which was included in Appendix B. The results of the query and the Microsoft® Access (2000) Wizard used to generate the report from the query were also included in Appendix B. The data describing the damage to the bridge were not stored in the current Pontis™ database but were uniquely identified using Pontis™ attributes (bridge number, span number and element type). Therefore, the data could be linked to the existing Pontis™ database through such Pontis™ attributes.

EXISTING DAMAGE ON A SPECIFIC BRIDGE

Bridge # 150107

Prestressed concrete submerged pile # 1 NW on span 52 has the following damage(s):

- Crack damage located above MLW
  crack length = 47 inch
  crack class = 2 class

Prestressed concrete submerged pile # 3 E on span 13 has the following damage(s):

- Longitudinal reinforcement corrosion damage located below MLW (-3 ft or more)
  reinforcement cross section loss = 100 percent
- Spall damage located below MLW (-3 ft or more)
  spall length = 43 inch
  spall width = 16 inch
  spall depth = 3 inch

Prestressed concrete submerged pile # 6 E on span 6 has the following damage(s):

- Longitudinal reinforcement corrosion damage located above MLW
  reinforcement cross section loss = 100 percent
- Spall damage located above MLW
  spall length = 39 inch
  spall width = 20 inch
  spall depth = 4 inch

Prestressed concrete submerged pile # 8 SE on span 12 has the following damage(s):

- Spall damage located below MLW (0 ft to -3 ft)
  spall length = 16 inch
  spall width = 6 inch
  spall depth = 1 inch

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Figure 4.7 Report Generated Using Data Stored on the "Damage", "Sectiondef", "Damagedef", "Parameterdef" and "Elementdef" Entities

The fact that this report could be generated from data stored in the model proved that data from detail inspection data could be maintained in an electronic format compatible with the Pontis™ database. The data highlighted in the report and shown in Figure 4.7 were used in the following two examples.

Example 4.2. Amount of a Specific Type of Damage on a Given Bridge Element

The second query retrieved a value for a given type of damage and for a specific element on a bridge defined by the user. The amount of damage triggered the model to select construction tasks. As an example, a concrete pile with longitudinal reinforcement corrosion was considered. Pile 6 on span 6 of bridge number 150107 was examined and the query retrieved the amount of cross section loss due to longitudinal reinforcement corrosion. The results of the query, shown in Figure 4.8, indicated that the amount of cross section loss due to corrosion of the longitudinal reinforcement was 100 percent. Since the cross section loss was more than 25 percent, the model selected construction tasks to provide additional reinforcement.

The query discussed in this example related the Pontis™ condition state with a quantitative value that defined the amount of damage in the element. In this example, the Pontis™ condition state of the element was 4 (***stkey*** attribute), and the amount of cross section loss due to corrosion of the longitudinal reinforcement was 100 percent. Therefore, this query proved that Pontis™ condition states could be re-defined using quantitative terms instead of a generic description of the damage.

elemID	spankey	elemdef	stkey	damdef	parameterdef	value	unit
6	6	Prestressed concrete pile	4	Longitudinal reinforcement corrosion	reinforcement cross section loss	100	percent

Figure 4.8 Results of Query #2 as Generated by Microsoft® Access (2000)

Example 4.3 Calculate the Spall Volume for a Given Bridge Pile

As a third example, a concrete pile with spall damage on a given bridge was considered. To calculate the MLE quantities of repairing a spalled area, the spall depth, width and length must be known. This query calculated a volume by multiplying the spall dimensions and stored the value of such volume in the variable “plan”. The model used this volume value to estimate the actual volume of concrete to be removed as discussed in Section 4.4.1 using neural networks. Considering the same concrete pile used to illustrate Example 4.2, the spall depth, length and width were 4 inches, 39 inches and 20 inches respectively. These dimensions were recorded in a detailed inspection report and were stored in the damage assessment model in the “damage” entity. As shown in Figure 4.9, query three retrieved these values and calculated the value of the variable “plan” as 3120 inches^3. This query proved that detailed inspection data stored in the Damage Assessment Model could be retrieved to calculate repair quantities. The SQL code used for this query was included in Appendix B.

brkey	elemID	spankey	damageloc	spall depth	spall length	spall width	plan
150107	6	6	E	4	39	20	3120

Figure 4.9 Results of Query #3 as Generated by Microsoft® Access (2000)

4.4 Conclusions

The data modeling presented in this chapter demonstrated that detail inspection data could be stored in a database that is compatible with the existing Pontis™ databases maintained by the state DOTs. Such data modeling associated quantitative damage values with each Pontis™ condition state definition. The data could be retrieved and manipulated using SQL queries created with Microsoft® Access (2000).

CHAPTER V

CONSTRUCTION PROCESS MODEL

5.1 Introduction

This chapter provides a methodology to define construction tasks at the pre-design stage. Specific research objectives accomplished in this chapter are: (1) define specific repair options for each bridge element defined in the Pontis™ database; (2) locate and collect the current technology knowledge and regulations used to repair concrete bridge piles; (3) define construction tasks required to repair concrete bridge piles; (4) model the logic behind the construction process for different repair methods for concrete bridge piles; and (5) select construction tasks based on bridge site-specific data and quantitative damage values. These objectives are related to the research methodology section highlighted in Figure 5.1

In Pontis™, each element on a given condition state had at most three maintenance repair and rehabilitation (MR&R) options. For concrete pile elements such options were “replacement”, “repair” or “do nothing”. Such definitions did not specify the repair method or the existing damage in the element. In contrast, the Construction Process Model related specific repair methods for each element in the Pontis™ database using seven repair matrices created by the author as shown in Figure 5.2(a).

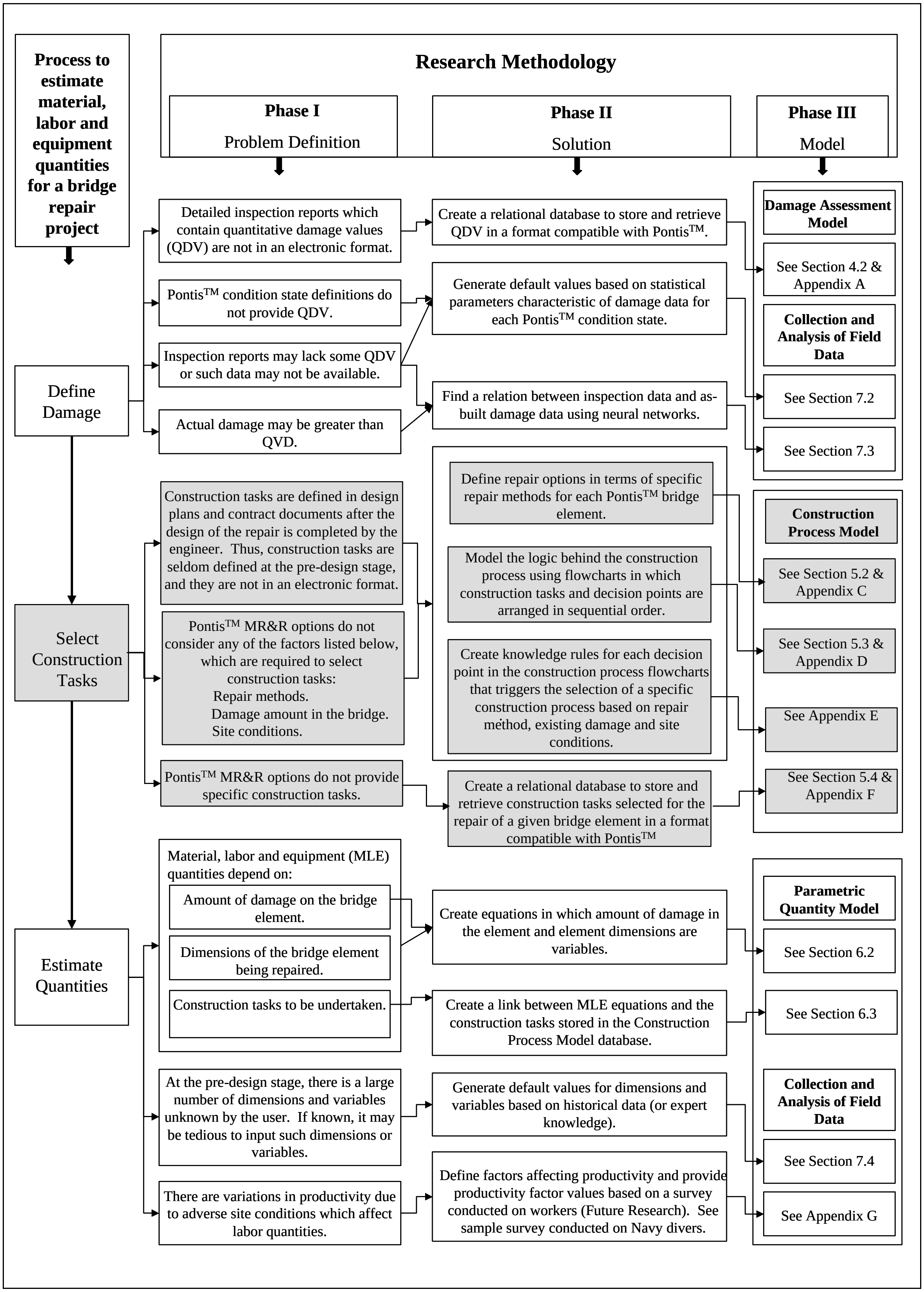

Figure 5.1 Research Methodology

Pontis™ Element	Add/replace reinforcement – fiberglass composite strips	Add/replace reinforcement – carbon fiber composite strips	Add/replace reinforcement – external post-tensioned FRP	Add/replace reinforcement – internal ungrouted post-tensioned FRP	Add/replace reinforcement – internal grouted post-tensioned FRP	Add/replace reinforcement – external post-tensioned steel strands	Add/replace reinforcement – internal ungrouted post-tensioned steel strands	Add/replace reinforcement – internal grouted post-tensioned steel strands	Add/replace reinforcement – external post-tensioned steel rebar	Add/replace reinforcement – internal ungrouted post-tensioned steel rebar	Add/replace reinforcement – internal grouted post-tensioned steel rebar	Add/replace reinforcement – fiberglass composite wraps	Add/replace reinforcement – carbon fiber composite wraps	Add/replace reinforcement – steel rebar cage	Add/replace reinforcement– lap weld rebar	Add/replace reinforcement – wire mesh	All polymer encapsulation	Integral CP jacket with sacrificial anode mesh	Integral CP jacket with titanium impressed current anode mesh	Encapsulation with removable form or jacket	Hybrid fiber epoxy composites
204	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
226	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
233	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1
205	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
210	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
215	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1
220	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
227	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 5.2(a) Partial View of the Element-Repair Method Matrix for Concrete Elements

Such repair matrices included Pontis™ elements and repair methods that were outside the scope of this research defined in Section 1.3. However, they were included in the matrices to provide a “big picture” of the model by defining the cases that should be considered in order to include all Pontis™ elements with their respective repair options. As an example, Pontis™ element 204, a prestressed concrete pile, was included in the scope of the research, while Pontis™ element 233, a prestressed concrete cap, was not included in the scope of the research, but it was included in the matrix. A description of the Pontis™ elements is provided in Figure 5.2(b). Pontis™ elements 204, 205, 226 and 227 were the only Pontis™ elements considered within the scope of this research and are shown in bold font in Figures 5.2(a) and (b).

Pontis Item	CoRe Element (Pontis) Description	NBI Item Number	NBI Item Description	Material
204	**P/S Concrete – column or pile extension (EA)**	60	Substructure	Prestressed Concrete
226	**P/S Concrete – submerged pile (EA)**			
233	P/S Concrete – cap (EA)			
205	**Reinforced concrete – column or pile extension (EA)**	60	Substructure	Concrete
210	Reinforced concrete – pier wall (m)			
215	Reinforced concrete – abutment (m)			
220	Reinforced concrete – submerged pile cap/footing (EA)			
227	**Reinforced concrete – submerged pile (EA)**			
234	Reinforced concrete – cap (m)			

Figure 5.2(b) Description of Concrete Elements Listed in Figure 5.2(a)

To illustrate the methodology, the author defined only construction tasks for each one of the repair options and Pontis™ elements included in the scope of the research. Construction tasks were further subdivided into construction subtasks. The construction process was modeled using flowcharts that incorporated the construction tasks and subtasks previously defined. Given the damage existing on the element under consideration, the specific site conditions and the repair method selected, the model used the flowcharts to select construction tasks and subtasks that applied to the specific element under consideration. The construction tasks definition and the construction process logic used by the Construction Process Model were not part of the current Pontis™ database. The author linked the construction tasks and subtasks definitions of the Construction Process Model to the Pontis™ attribute defining the type of element. This was done to make the model compatible with the existing Pontis™ database. Data used to define construction tasks and construction subtasks were modeled using the entity-relationship model.

5.2 Repair Matrices

The model listed possible repair options for each one of the Pontis™ elements using the knowledge data stored in seven repair matrices. These matrices were included in Appendix C. A portion of one of these matrices is shown in Figure 5.2(a). The Pontis™ bridge element included in the scope of this research were those corresponding to concrete piles (Pontis™ element 204, 205, 226 and 227) and are shown in bold font in Figure 5.2 (a) and (b). A description of these repair methods was included in the Background Chapter, and they are listed below.

- Integral CP jacket with sacrificial anode mesh
- Integral CP jacket with impressed current anode mesh
- All polymer encapsulation
- Hybrid fiber composite wraps

The repair matrix also provided a list of options for repair or replacement of reinforcement. In the repair matrices, the vertical axis corresponded to the Pontis™ element and the horizontal axis to the repair methods. The intersection of a horizontal axis with a vertical axis, could take a value equal to either "1" or "0". If the value shown was "1", the repair method listed in the vertical axis applied to the element listed in the horizontal axis. If the value was "0", the repair method did not apply to the element.

To illustrate the methodology, the same prestressed concrete pile used as an example in Chapter IV was used in this chapter. This pile was pile number 6 located on span 6 of the Howard Frankland Bridge. The FDOT Bridge Number was 150107. The bridge carried interstate I-275 over the Old Tampa Bay. The Pontis™ element used to classify the pile was 226. According to FDOT design plans, the repair method selected was an integral CP jacket with a sacrificial zinc anode. The reinforcement repair method selected was to add a cage of mild steel reinforcing bars. Both repair methods were highlighted in Figure 5.2 (a)

5.3 <u>Construction Process Flowcharts</u>

Once the user selected the type of repair and element being repaired, the model used construction flowcharts to define the construction processes.

Figure 5.3 describes the nomenclature used in the flowcharts. In the model, the construction tasks were organized in modules that could be used by any of the repair methods under consideration. Rectangular boxes with a double line border represented these modules. This was done to maintain the modularity of the model and to facilitate the implementation of a software system later. In all the flowcharts, the activities shown in a rectangular box with a single line border represented the construction subtasks. Beside each box, there was a two number combination used to identify the construction subtasks. The first number represented the construction task identification code (taskID), and the second one represented the construction subtask identification number (subtaskID). Table 5.1 provides a partial sample of construction tasks and subtasks considered in the flowcharts. The rest of the construction tasks and subtasks considered are listed in Table D.1, which is included in Appendix D. In the flowcharts, an asterisk beside a construction task identification box indicated that such construction subtask might apply to a group of elements. The rationale was that there were construction tasks that needed to be done only once for a group of elements. The author recommended giving the user the option to group elements that could be repaired together. Then, the model could recognize construction tasks that applied to a group of elements and include such construction activities only once. Within the same project the user should have the option to create different groups that apply to different construction tasks. The author did not implement a tool to group elements, to count elements in a group or to differentiate between elements in different groups. However, the author assumed that such a grouping tool would allow the model to recognize which was the first and last element in the group being repaired. The first and last elements of a group were used to trigger the execution of knowledge rules. The need for such a tool was discussed to facilitate the implementation of a software development later.

The decision points, represented by a diamond box in Figure 5.3, were identified using a two-number combination, which was displayed in the oval box adjacent to the decision box. The first number identified the module and the second number the decision point within the module.

Module Selection Flowchart

The module selection flowchart was used to select construction tasks (grouped in modules) required to install the repair systems discussed in Chapter II.

The parameters required by the module selection flowchart were:

- Type of element (Pontis™ attribute, stored in the Damage Assessment Model).
- Type of repair (user input). The user selected the type of repair from the options provided by the model (see repair matrices).

For the example discussed, the type of Pontis™ element was 226 and the type of repair selected by the FDOT to repair the pile was an integral CP jacket with sacrificial zinc anodes.

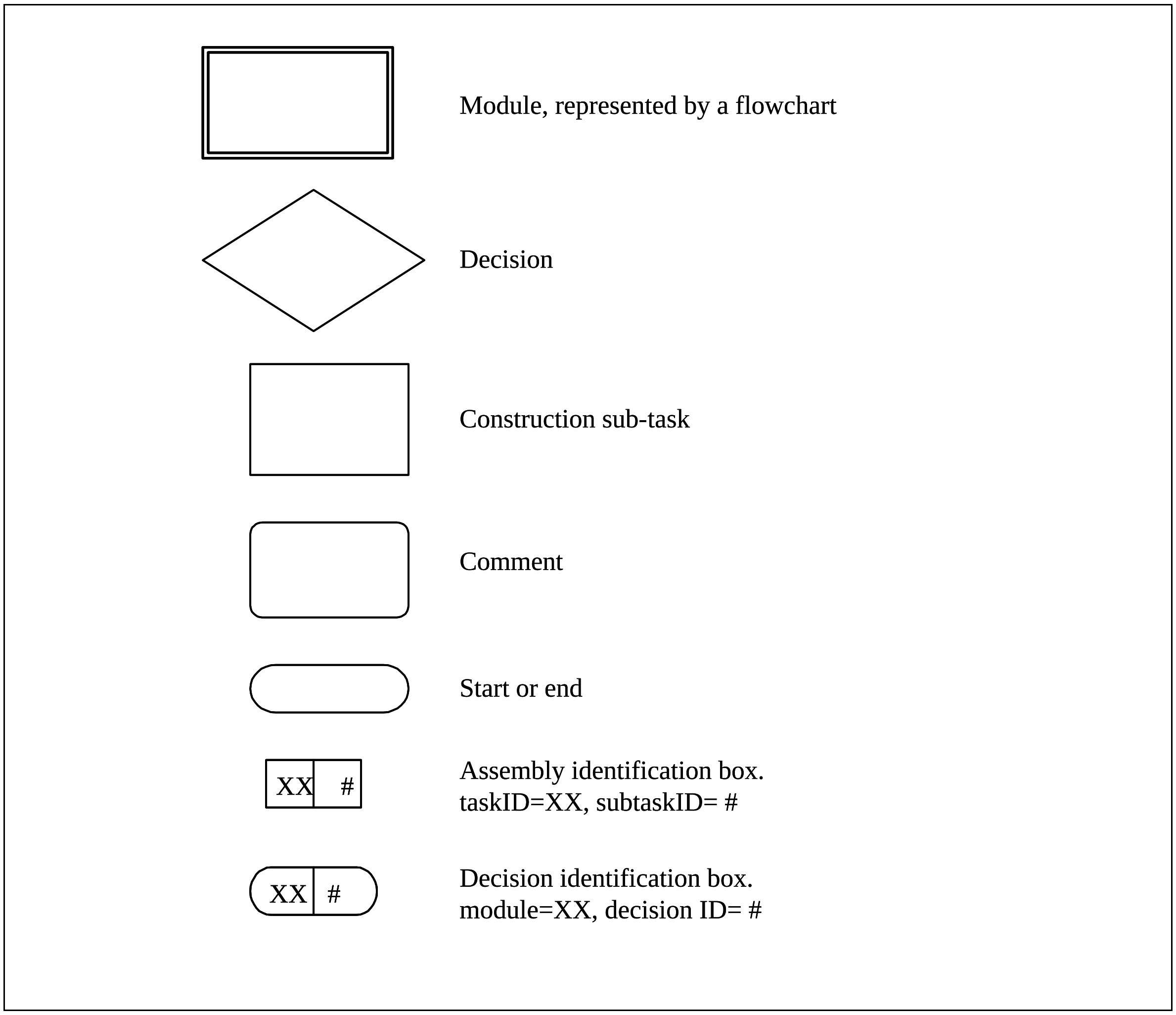

Figure 5.3 Nomenclature Used in the Construction Process Flowcharts

Table 5.1 Sample Construction Tasks and Subtasks Described in the Construction Process Flowcharts

Task Definition	Task Identification Task Identification ID	Subtask Definition	Subtask Identification Number
Protective Barriers Use	PB	Place floating protective barriers	1
	PB	Remove floating protective barriers	2
Concrete Removal	CR	Remove existing jacket	1
	CR	Remove existing anode	2
	CR	Sound test concrete area	3
	CR	Remove large pieces of unsound concrete	4
	CR	Remove loose particles	5
	CR	Dispose of debris	6
	CR	Clean pile surface	7
	CR	Saw cut concrete to make a small excavation	8
	CR	Remove concrete to make a small excavation	9

The module selection flowchart is shown in Figure 5.4. Once the user selected the repair method from the options proposed by the repair matrices, the model used the decision matrix shown in Figure 5.5 to gather default values for the decision points required by the module selection flowchart. The default values for CP jackets with sacrificial zinc anodes are shown highlighted in Figure 5.5. Such default values resulted in a construction process that included the modules highlighted in Figure 5.4, which are also listed below:

1. Pile access.
2. Concrete removal.
3. Reinforcement repair.
4. Continuity testing.
5. Continuity bonding.
6. Reference cell installation.
7. Formwork placement.
8. Grout mobilization.
9. Grout casting.
10. Formwork removal.

The modules selected by the model were also flowcharts. To illustrate the methodology, such flowcharts were described below. For each decision point in the flowcharts, the author created knowledge rules, which combined data stored in the model and user input data ("parameters") to trigger the model to select construction tasks. Such knowledge rules were included in Appendix E.

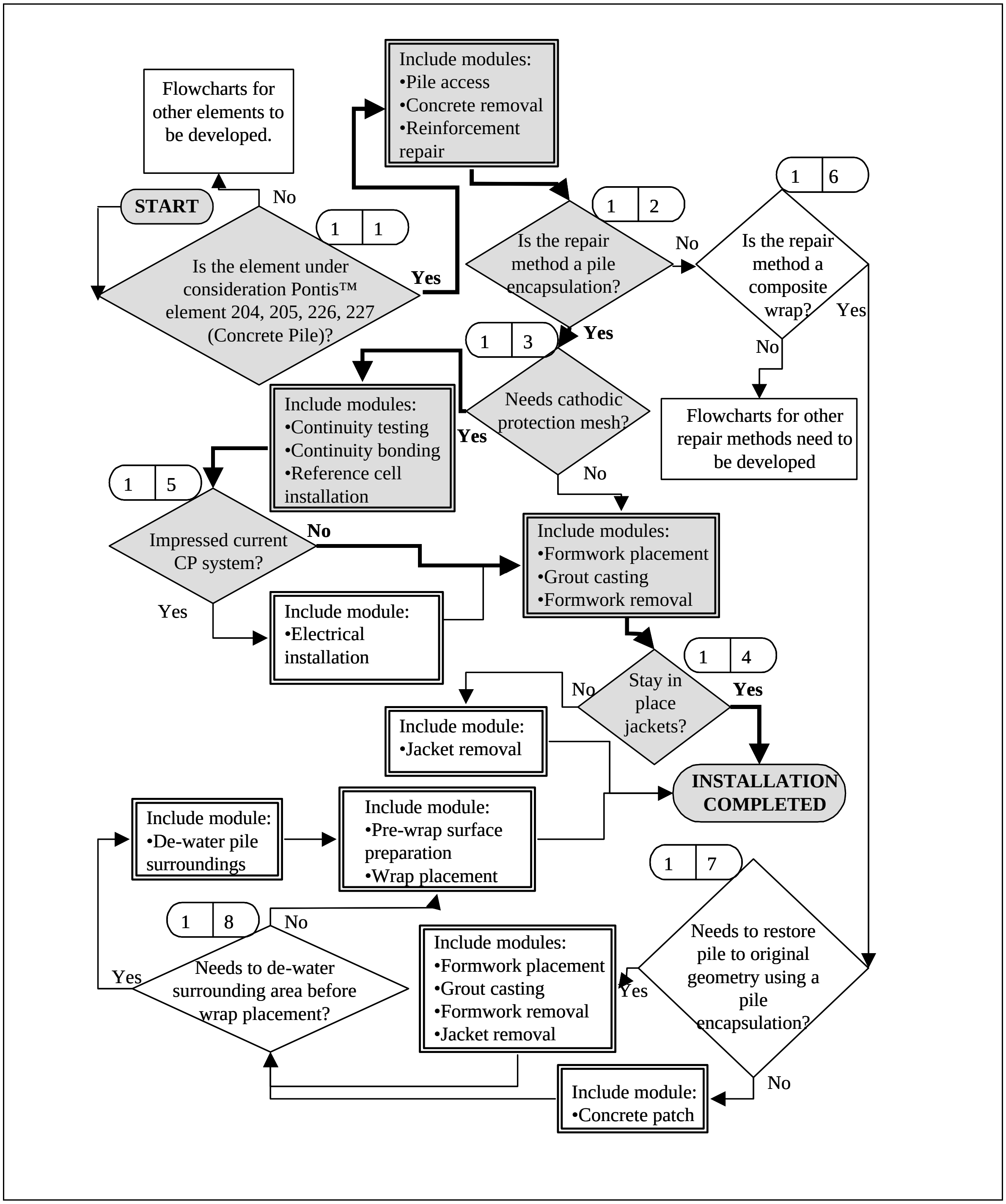

Figure 5.4 Module Selection Flowchart

Decision Point / Repair Method	1	2	3	4	5	6	7	8
CP Integral Jacket with Sacrificial Anodes	Y	Y	Y	NA	N	NA	NA	NA
CP Jacket with Impressed Current	Y	Y	Y	NA	Y	NA	NA	NA
All Polymer Encapsulation	Y	Y	N	Y	NA	NA	NA	NA
Composite Wrap	Y	N	NA	NA	NA	Y	Y	N

Figure 5.5 Default Values for the Decision Points Shown in the Module Selection Flowchart
"Y"=Yes, "N"=No, "NA"=Not applicable.

<u>Pile Access Module Flowchart</u>

The parameters that were required by the system to make decisions using this flowchart included:

- Type of environment around the pile (user input). The user had to select among the following options (user options): waterway, roadway or other.
- Type of access (user input). User options: fenced or free.
- Damage location (Damage Assessment Model).

The pile access module flowchart is shown in Figure 5.6. If the type of environment around the pile was water, then the pile accessibility matrix, shown in Figure 5.7 provided the user with options to access the pile based on the section where the damage was located and the water depth.

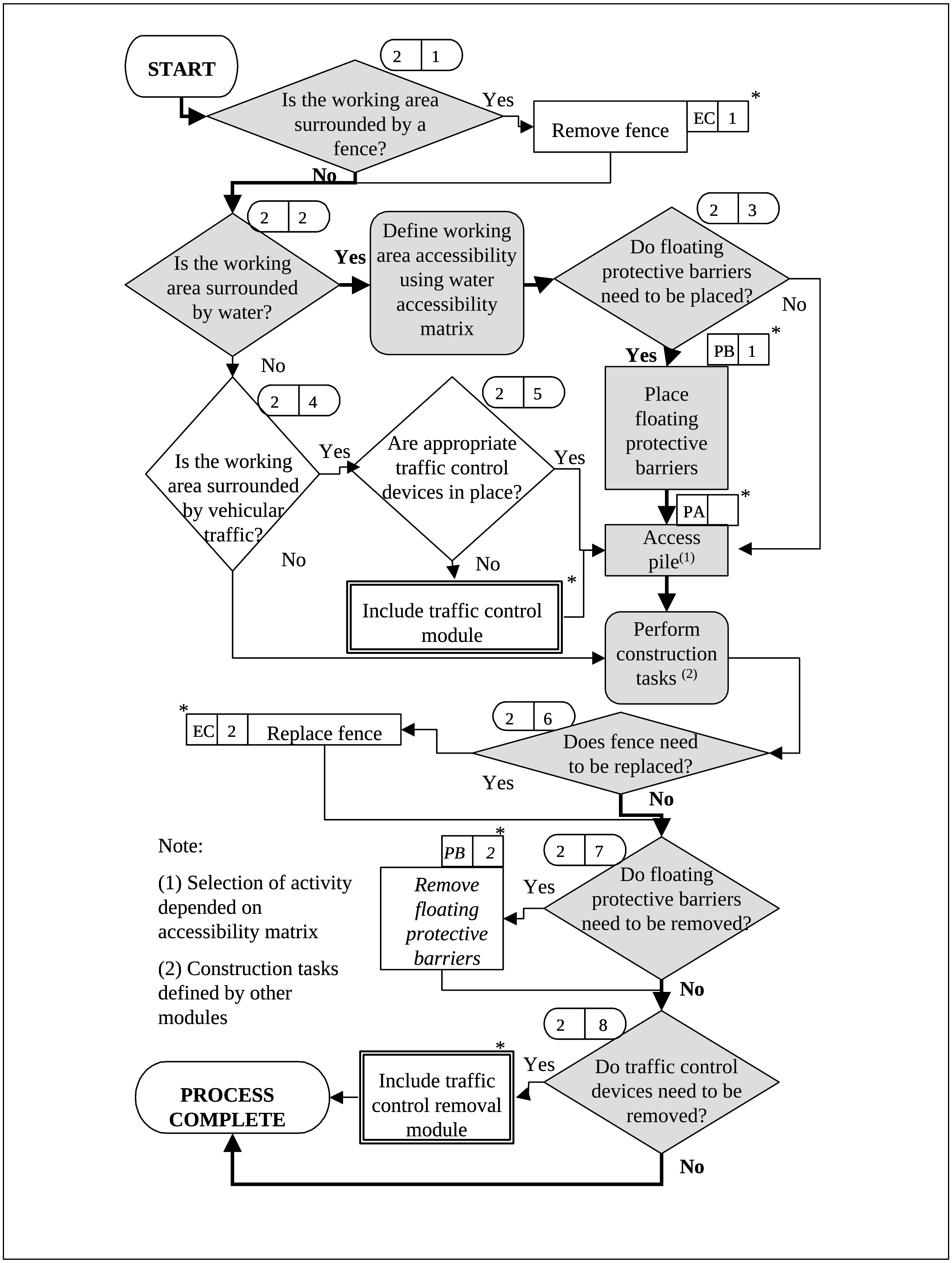

Figure 5.6 Flowchart Used by the Pile Access Module

Damaged Area / Water Elevation (feet)	Above MLW (*i* =1)	Below MLW (< 3 feet) (*i* =2)	Below MLW (> 3 feet) (*i* =3)
0	Walk	Not applicable	Not applicable
0 < Water Elevation = 1	Walk	Walk	Not applicable
1 <Water Elevation = 3	Platform	Walk / Snorkeling	Not applicable
3 < Water Elevation = 5	Platform	Walk / Snorkeling	Walk / Scuba diving
Water Elevation > 5	Platform	Platform / Snorkeling	Platform / Scuba diving

Figure 5.7 Pile Accessibility Matrix

The water depth was a user input value. The damage location was stored in the model using the attribute *i* of the "damage" entity described in the Damage Assessment Model (see Table 4.7) which defined the section in the element where the damage was located. The "sectiondef" entity provided a description for each one of those sections (see Table 4.4).

For the example, prestressed concrete pile 6 on span 6 of bridge 150107, the author gathered the input data required by the model from FDOT design plans of the repair project as follows. The type of service under the bridge was a waterway; the type of access was free. The author did not have existing plans for the Gandy Bridge and was not able to obtain them. Instead, the author visited the Gandy Bridge, and by visually inspecting the water elevation was able to infer that the water depth was greater than five feet. The damage data were gathered from a FDOT detailed inspection report, and stored in the Damage Assessment Model. The damage was located above MLW (see report shown in Figure 4.7 and data highlighted in Tables 4.4 and 4.7).

According to the FDOT design plans, an intermediate pile bent had 8 piles. For this particular example, the author assumed that all the piles in the pile bent of span 6 were repaired at the same time, and that the pile used in the example was the first pile being repaired. This assumption was made because in the flowcharts there were construction tasks that applied to a group of elements. As an example, according to the pile access module flowchart, if the pile was submerged in water, then floating protective barriers should be placed. Such a barrier was placed around a group of piles (defined by the user). The author assumed that the construction activity of placing the construction barrier was performed before the first pile in the group was repaired, and it was removed after the last pile in the group was repaired. This assumption was used in the knowledge rule for decision points (2-3) and (2-7) discussed in Table E.1. Construction task (PB-1) which was "place floating protective barriers" was included when the example pile was repaired (shown highlighted in Figure 5.6) because, as discussed earlier, the author assumed that the example pile was the first pile in the group of piles being repaired. On the other hand, the construction task (PB-2) which was "remove floating protective barriers" was not included when the example pile was repaired but when the last pile was repaired. Construction activity (PB-2) was shown in italic font to indicate that the construction activity would be included later for another pile in the group (last pile in the group). The same convention was used in the other flowcharts when highlighting activities that referred to the example pile. Using the input parameters described, and the knowledge rules described in Appendix E, Table E.1, the model selected the construction process highlighted in Figure 5.6, which included the following construction tasks:

- PB-1 = Place floating protective barriers.
- PA-5 = Access pile using a platform.
- PB-2 = Remove floating protective barriers.

For the example discussed, the option provided by the pile accessibility matrix was to access the pile with a platform, shown highlighted in Figure 5.7.

Concrete Removal Module Flowchart

The flowchart used by the concrete removal module is shown in Figure 5.8. For concrete pile elements (Pontis™ element 204, 205, 226 and 227), the parameters that were required by the decision points of the concrete removal module flowchart included:

- Type of protection systems already installed on the pile (user input). User options: jacket, anode, none.
- Type of repair method (user input). This parameter was already selected by the user from a list of options generated from the repair matrices discussed earlier. For a concrete pile such options were:

  Option 1: Integral CP jacket with sacrificial anode mesh.

  Option 2: Integral CP jacket with impressed current anode mesh.

  Option 3: All polymer encapsulation.

  Option 4: Hybrid fiber epoxy composites.
- Dimensions of unsound concrete area (Damage Assessment Model).

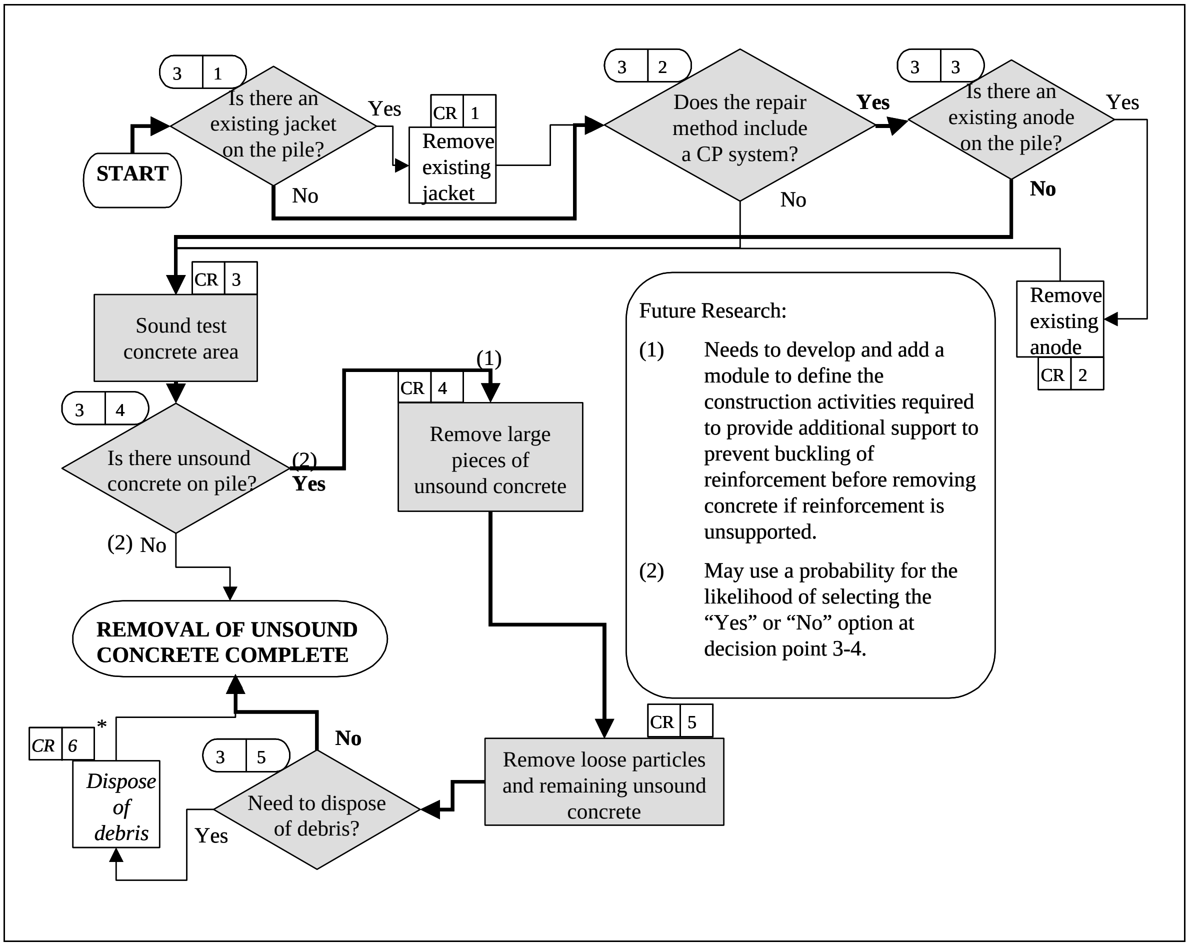

Figure 5.8 Flowchart Used by the Concrete Removal Module

For the pile used as an example to illustrate the methodology, there was not a protection system installed. The repair method was an integral CP jacket with sacrificial anode mesh. There was unsound concrete on the pile. The dimensions of unsound the concrete were retrieved from the Damage Assessment Model using the query described in Example 4.3. Such query listed the spall depth, spall length and spall width as 4 inches, 39 inches and 20 inches. These parameters and the knowledge rules described in Appendix E, Table E.2 were used to define the construction process for the specific example pile, which is shown highlighted in Figure 5.8 and includes the following construction tasks:

CR-3 = Sound test concrete area.

CR-4 = Remove large pieces of unsound concrete.

CR-4 = Remove loose particles and remaining unsound concrete.

CR-6 = Dispose of Debris.

Reinforcement Repair Module Flowchart

The parameters that were required by the system to make decisions include:

- Corrosion data (damage assessment). The model needed to know whether there was corrosion or not. If there was corrosion, then the model needed to know the amount of reinforcement cross section loss.
- Type of reinforcement in the pile (user input). User options: prestressed steel strands, mild steel reinforcing bars, default.
- Type of additional/replacement reinforcement (user input). User options were those shown in the repair matrices and consisted of adding or replacing:

1. Steel rebar cage.
2. Lap weld rebar.
3. Wire mesh.
4. External post-tensioned steel strands.
5. Internal ungrouted post-tensioned steel strands.
6. Internal grouted post-tensioned steel strands.
7. External post-tensioned fiber reinforced plastic (FRP).
8. Internal ungrouted post-tensioned FRP.
9. Internal grouted post-tensioned steel FRP.
10. External post-tensioned steel rebar.

11. Internal ungrouted post-tensioned steel rebar.

12. Internal grouted post-tensioned steel rebar.

13. None.

14. Default (steel prestressed strands).

The default value for the reinforcement in the pile was steel prestressed strands. The default value was defined as steel prestressed strands because it was the most common type of reinforcement observed in 1,475 piles (twenty bridges) analyzed. In this sample 84 percent of the piles had steel prestressed reinforcement and only 16 percent mild steel reinforcing bars. Similarly, if the type of reinforcement replacement was not defined by the user, by default, the model assumed that mild steel reinforcing bars were used as reinforcement replacement because it was the most common type of replacement reinforcement observed in 588 piles (seven bridges) analyzed. In this sample 53 percent of the piles had mild steel reinforcing bars used as reinforcement replacement and 47 percent had steel mesh.

For the example pile (pile 6 span 6 of bridge 150107), there was 100 percent reinforcement cross section loss. See Figure 4.7 and Example 4.2. According to FDOT design plans, the reinforcement in such a pile were prestressed steel strands, and the type of additional reinforcement was steel rebar cage. These parameters and the knowledge rules described in Appendix E, Table E.3 were used to define the construction process for the specific example pile, which is shown highlighted in Figure 5.9 and includes the following construction tasks:

- RR-1 = Clean reinforcement.
- RR-4 = Form rebar cage.

- RR-5 = Place rebar cage around pile.
- CB-2 = Connect continuity wire between existing and new reinforcement.
- CR-7 = Clean pile surface.

Continuity Testing Module Flowchart

The continuity testing module flowchart, shown in Figure 5.10, did not require input parameters nor had decision points. If the continuity testing module was selected (see module selection flowchart, Figure 5.4), then all of the construction tasks shown in the flowcharts should be included. Such was the case for the example pile (see highlighted modules on Figure 5.4).

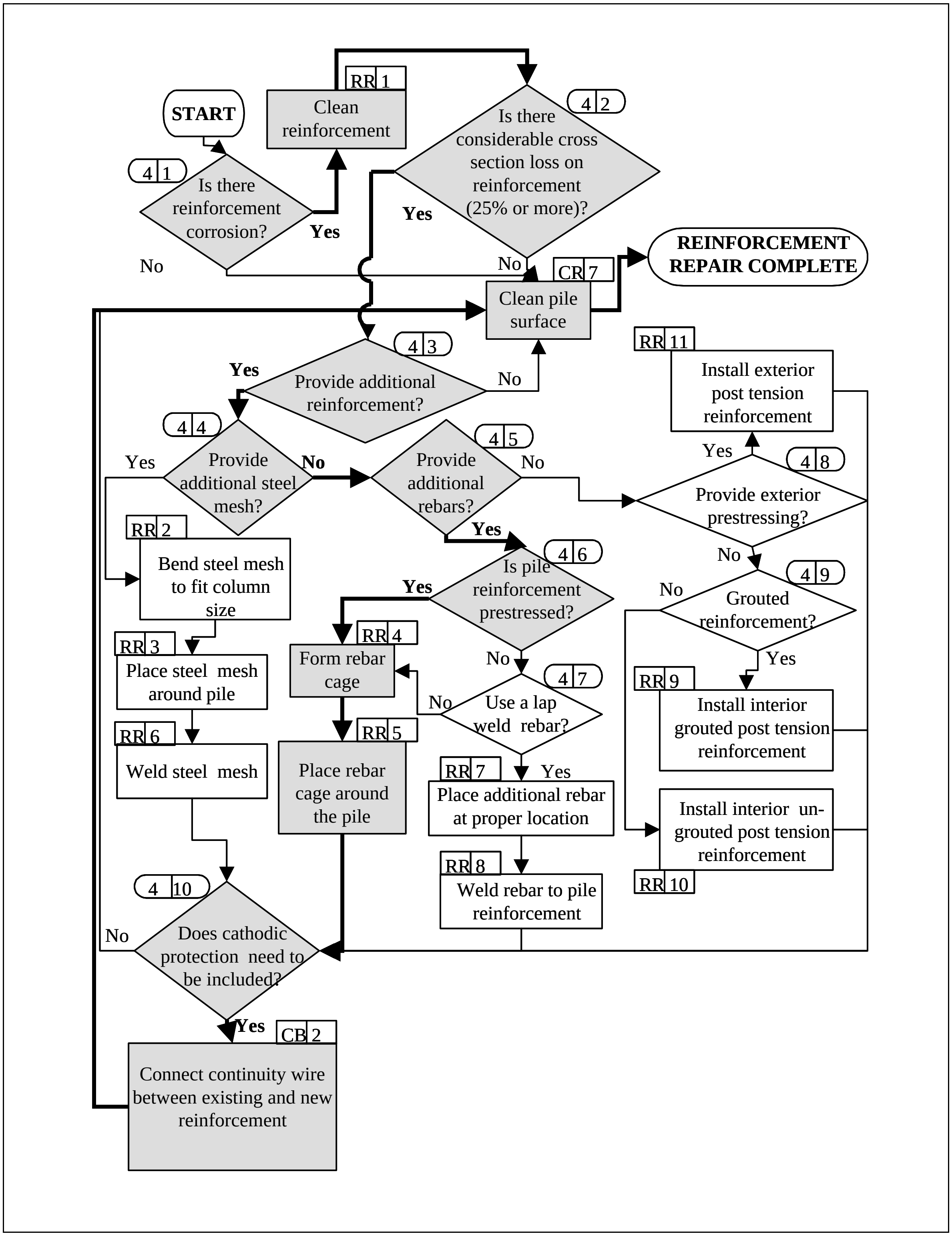

Figure 5.9 Flowchart Used by the Reinforcement Repair Module

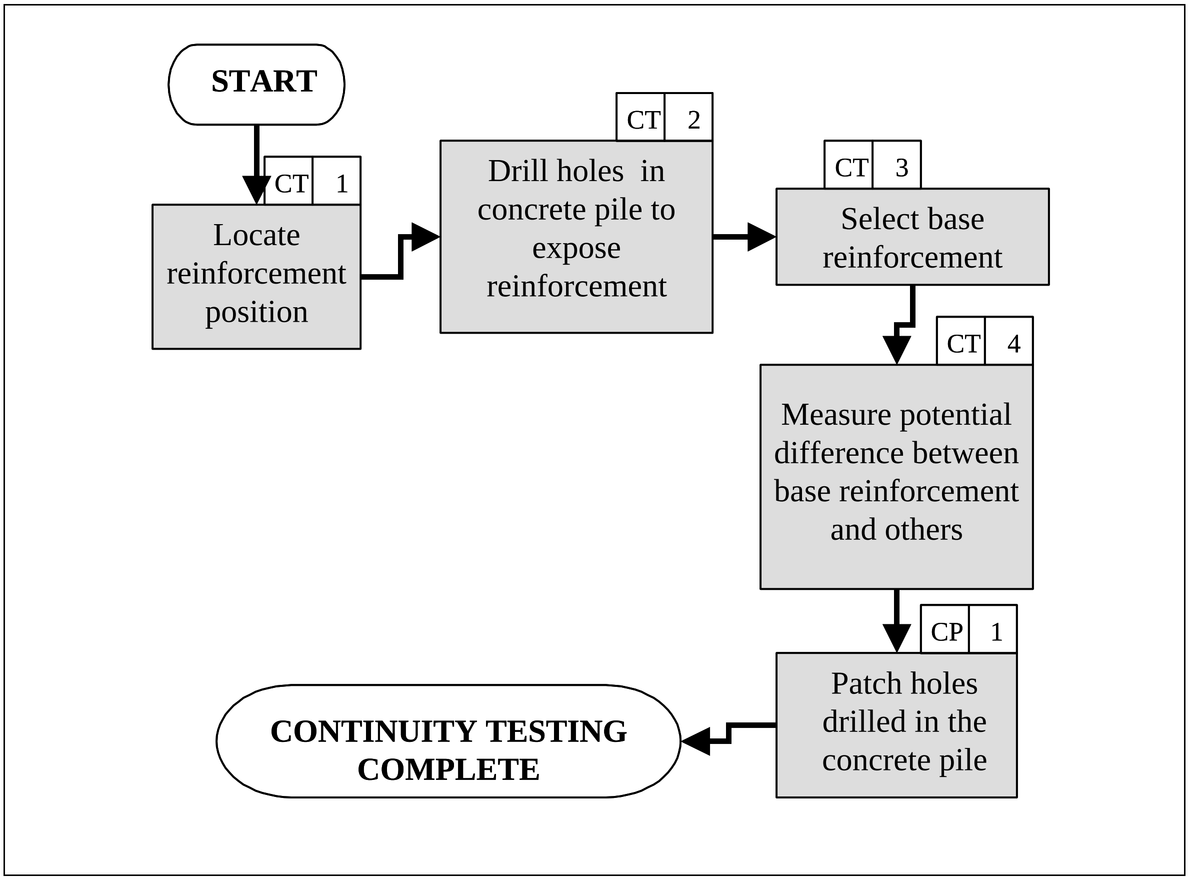

Figure 5.10 Flowchart Used by the Continuity Testing Module

Continuity Bonding Module Flowchart

The parameters required by the continuity bonding module flowchart include:

- Type of reinforcement in the pile (user input). User options: prestressed steel strands, mild steel reinforcing bars, default.
- Probability of having discontinuous strands on any column face (User input). The user could either provide a probability or use the default values stored in the model.

The parameters required by the continuity bonding module flowchart were empirical probabilities. Default values were proposed based on data analyzed by the author, and they are discussed in Chapter VII. Such default values have been organized in Tables E.4 and E.5 according to the type of reinforcement on the pile. Table E.4 refers to piles with prestressed steel strands. Table E.5 refers to piles with mild reinforcement steel bars. For the example pile (pile 6 span 6 of bridge 150107) the type of reinforcement in the piles were prestressed steel strands. One of the possible construction process paths that could occur is shown highlighted in Figure 5.11. The probability that such a path could occur was shown in parentheses beside each decision point. The author did not implement a tool to generate a probabilistic estimate because it was outside the scope of the research. Probabilistic methods such as the Monte Carlo simulation use probabilities at each decision point to generate a range of values. Future research could implement such a tool using a Monte Carlo simulation in conjunction with the probabilities proposed in Tables E.4 and E.5.

If the construction process shown highlighted in Figure 5.11 occurred, then the following construction tasks would have been selected:

CB-1 = Locate area of concrete to be removed.

CR-8 = Saw cut concrete to make a small excavation.

CR-9 = Remove concrete to make a small excavation.

CB-4 = Connect continuity wires between existing pile reinforcement.

CB-3 = Weld negative connection to transverse reinforcement.

CP-2 = Cover welds with epoxy.

CP-3 = Restore small excavations on pile surface to original profile.

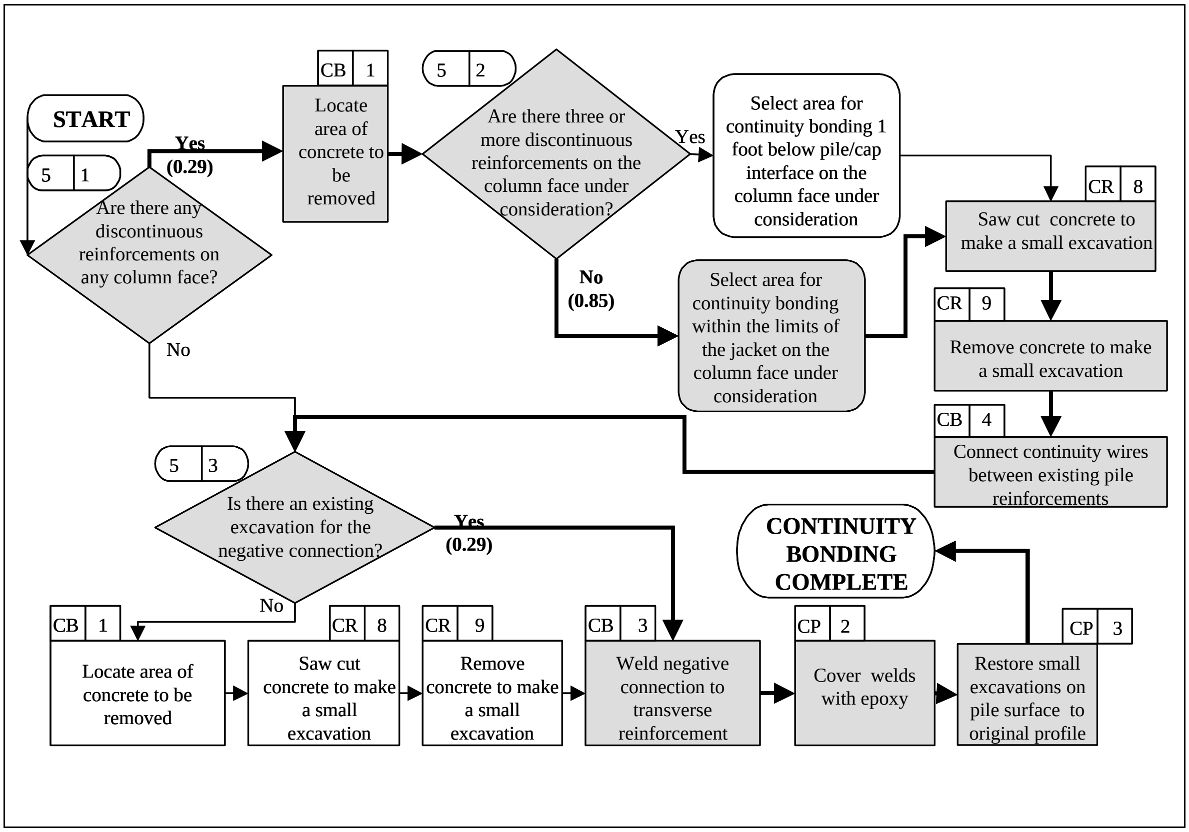

Figure 5.11 Flowchart Used by the Continuity Bonding Module

Reference Cell Installation Module Flowchart

The reference cell installation module flowchart, shown in Figure 5.12, did not require input parameters nor had decision points If the reference cell installation module was selected (see module selection flowchart, Figure 5.4), then all of the construction tasks shown in the flowcharts should be included. Such was the case for the example pile (see highlighted modules on Figure 5.4).

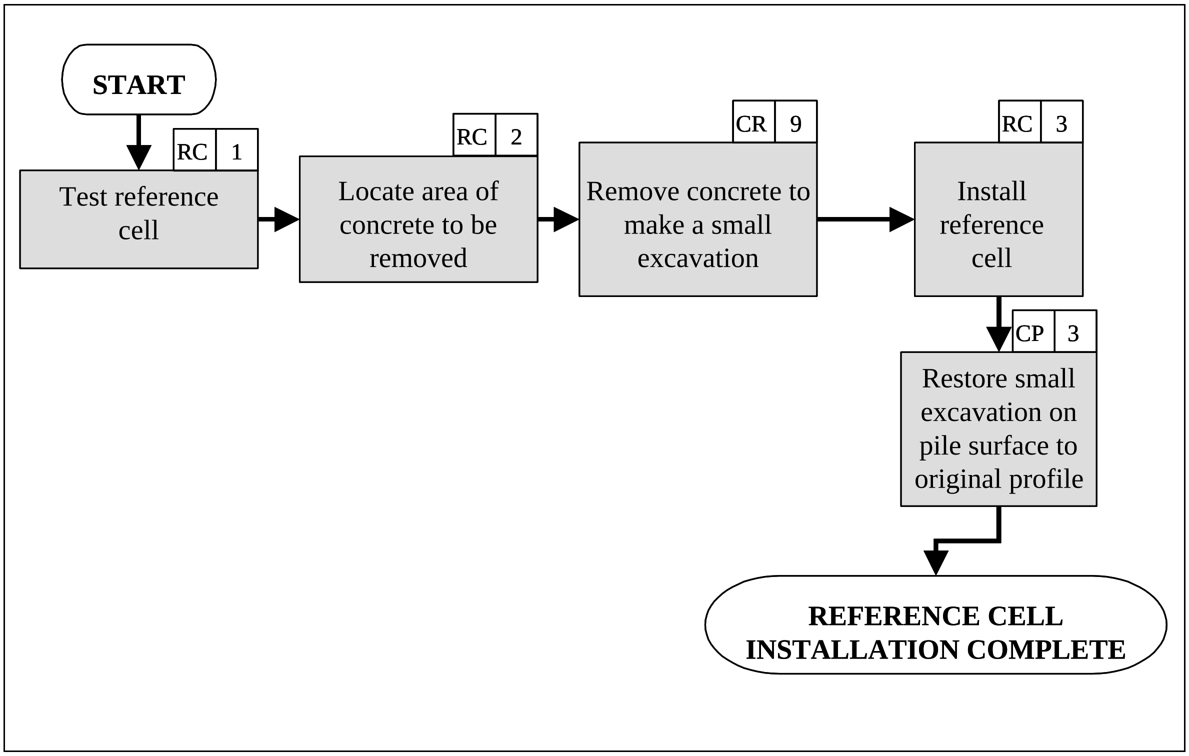

Figure 5.12 Flowchart Used by the Reference Cell Installation Module

Formwork Placement Module Flowchart

The flowchart used by the formwork placement module is shown in Figure 5.13. The parameters that were required by the system to make decisions include:

- Type of formwork used (user input). User options: bottom formwork only, lateral formwork only, bottom and lateral formwork, none.
- Existing soil elevation (user input).
- Bottom of jacket elevation (user input).

If the pile was surrounded by water, then the user was required to input the water elevation (MLW).

To reduce the amount of input data, the author suggested providing the user a tool to enter the data only once for all the piles being repaired.

The FDOT design plans of the repair project for the example pile (pile 6 span 6 of bridge 150107) required bottom and lateral formwork to be used. The bridge was over Tampa Bay. The author did not have existing plans for the Gandy Bridge and was not able to obtain them. Instead, the author visited the Gandy Bridge, and by visually inspecting the water elevation was able to infer that the water was deep enough to insure that the bottom of the jacket was located higher than soil elevation. The author used this assessment to define the output options for the formwork placement module. The knowledge rules described in Appendix E, Table E.6 were used to define the construction process for the specific example pile, which is shown highlighted in Figure 5.13 and includes the following construction tasks:

- FP-1 = Move formwork to working place.
- FP-2 = Measure bottom formwork position.
- FP-3 = Install bottom formwork.
- FP-4 = Install lateral formwork.
- FP-5 = Install lateral braces.

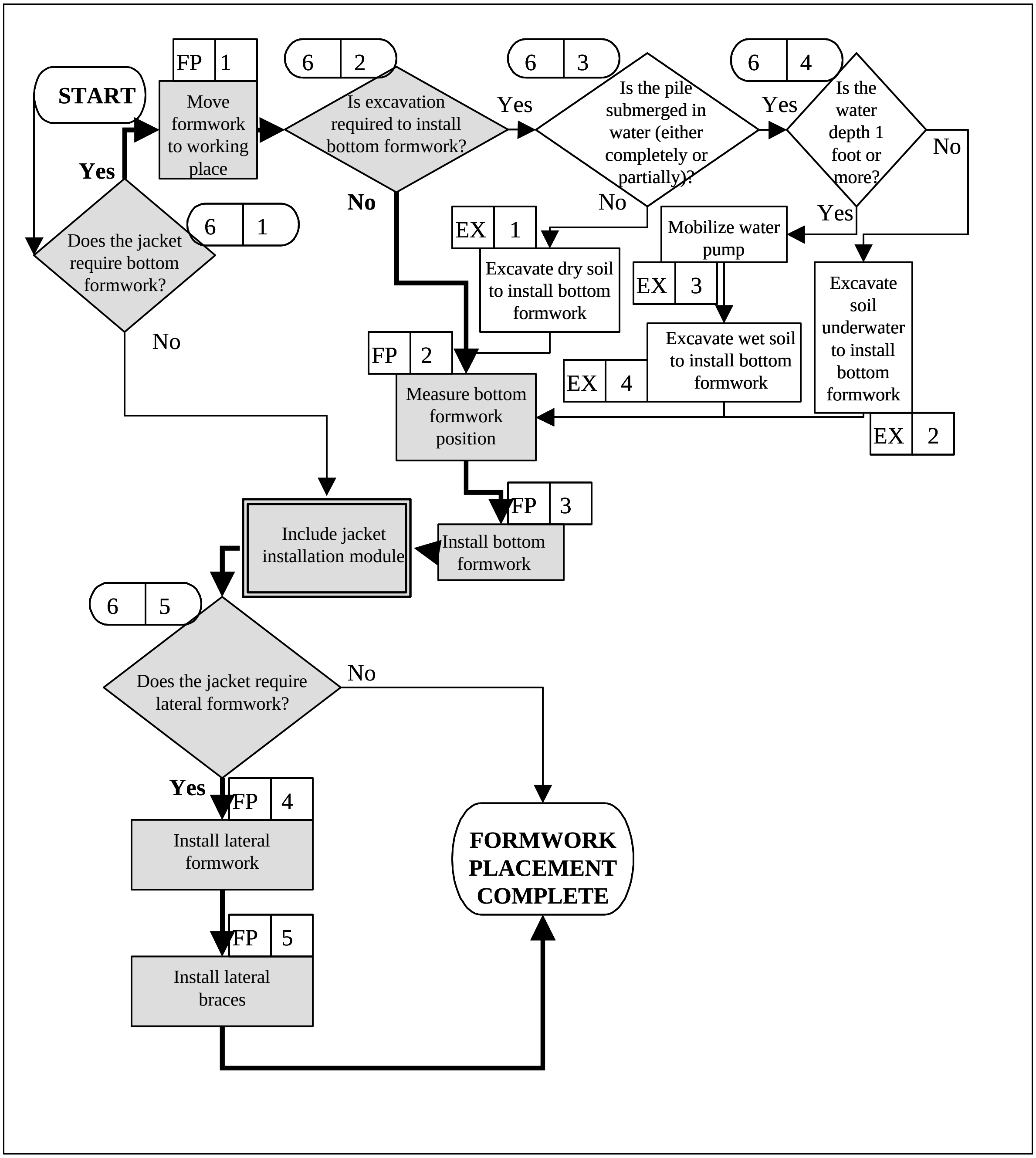

Figure 5.13 Flowchart Used by the Formwork Placement Module

Jacket Placement Module Flowchart

The only input parameter required by the jacket placement module was the type of repair and that was already selected because it was required for the module selection flowchart. The options provided to the user were:

Option 1: Integral CP jacket with sacrificial anode mesh.

Option 2: Integral CP jacket with impressed current anode mesh.

Option 3: All polymer encapsulation.

Option 4: Hybrid fiber epoxy composites.

The knowledge rules used by the decision points of the jacket placement module are described in Appendix E, Table E.7.

For the example pile (pile 6 span 6 of bridge 150107), the type of repair was an integral CP jacket with sacrificial anode mesh. The construction process for the specific example pile is shown highlighted in Figure 5.14, resulting in the selection of the following construction tasks:

- JP-1 = Mobilize jackets to bridge site.
- JP-2 = Move jackets to working place.
- JP- 3 = Place jackets at proper elevation.
- JP-4 = Apply epoxy to jacket seams.
- JP-5 = Snap jackets together.
- JP-6 = Insert jacket fasteners.

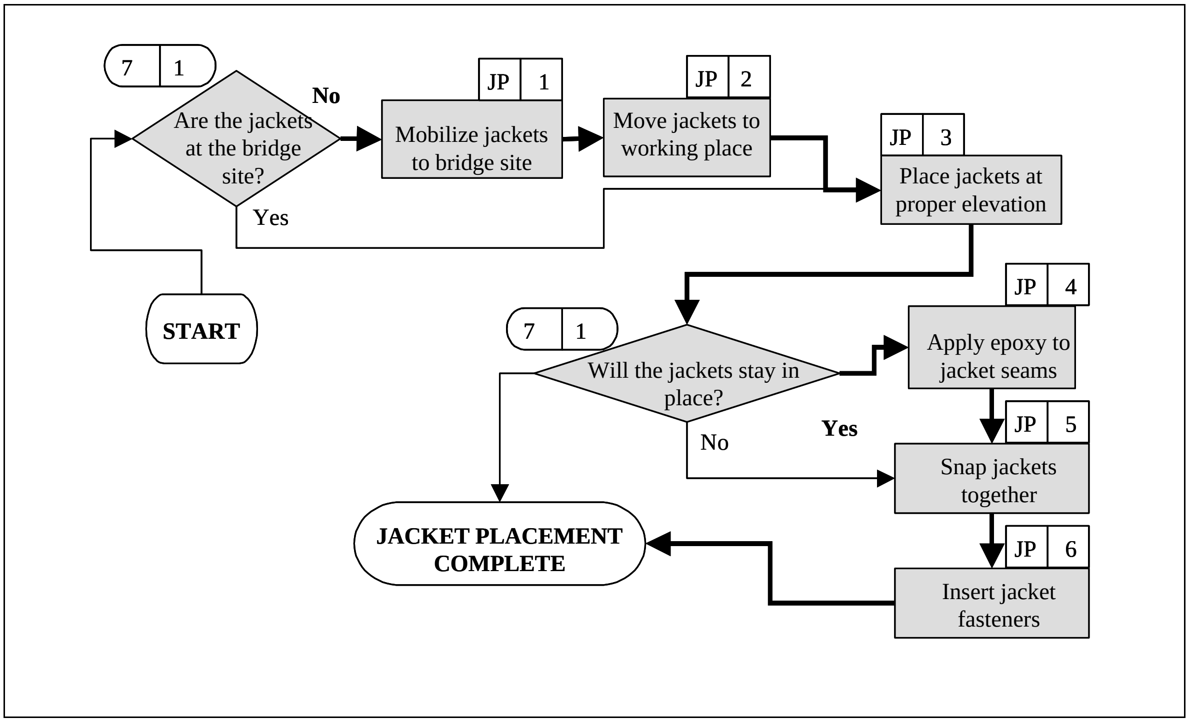

Figure 5.14 Flowchart Used by the Jacket Installation Module

Grout Casting Module Flowchart

The input parameters required by the grout casting modules were:

- Type of repair (user input). The user was required to enter this input for the module selection flowchart.

For the example pile (pile 6 span 6 of bridge 150107), the type of repair was an integral CP jacket with sacrificial anode mesh. The construction process for the specific example pile is shown highlighted in Figure 5.15 (see knowledge rules in Table E.8), resulting in the selection of the following construction tasks:

- GC-13 = Place grout hose at the bottom of the jacket.
- GC-14 = Pump grout until jacket is full of grout.

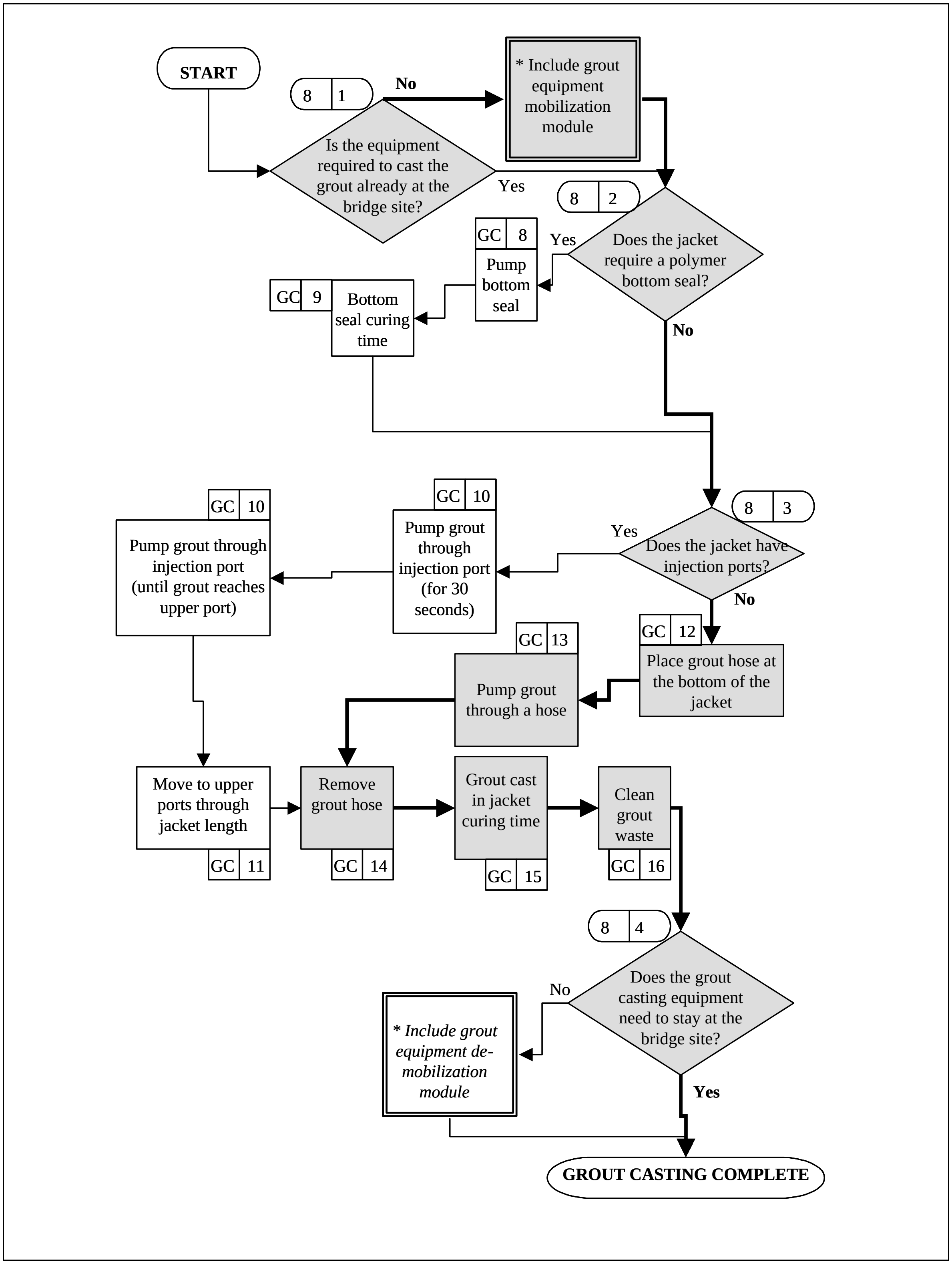

Figure 5.15 Flowchart Used by the Grout Casting Module

- GC-15 = Remove grout hose.
- GC-16 = Allow to cure for a specified amount of time.
- GC-17= Clean grout waste.

Grout Mobilization Module Flowchart

The input parameters required by the grout mobilization flowchart were:

- Type of grout (user input). User options: cement, polymer.
- Grout mixing location (user input). User options: in site, factory.

For the example pile (pile 6 span 6 of bridge 150107), the FDOT design plan required cement grout to be used. The grout mixing location was not specified in the design plans. To illustrate the example, the author assumed the grout was mixed at the factory. The construction process for the example pile is shown highlighted in Figure 5.16 (see knowledge rules in Table E.9). Such construction process included the following construction tasks:

- GC-2 = Mobilize grout truck to bridge site.
- GC-14 = Mobilize grout pump to bridge site.
- QC-1 = Quality control: slump test.
- QC-2 = Quality control: strength cylinder casting.

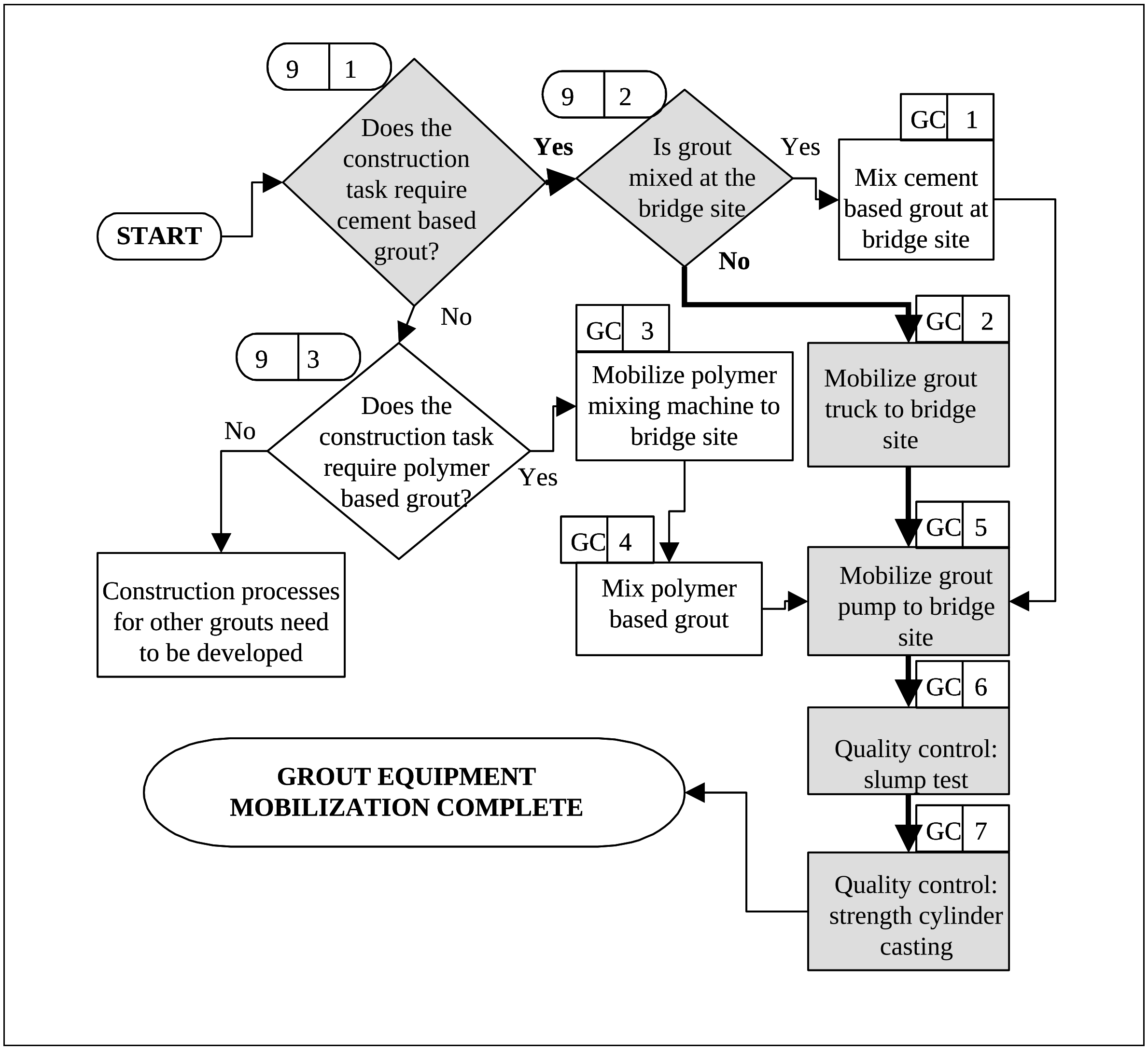

Figure 5.16 Flowchart Used by the Grout Mobilization Module

<u>Formwork Removal Module Flowchart</u>

The only parameter that was required by the system to make decisions was the type of formwork, which was already input by the user when required to select the input parameters for the formwork placement module flowchart.

As discussed earlier, for the example pile (pile 6 span 6 of bridge 150107), the FDOT design plan required bottom and lateral formwork to be used. The construction process for the example pile is shown highlighted in Figure 5.17 (see knowledge rules in

Table E.10). All construction tasks described in the formwork removal module flowchart were selected for the example pile.

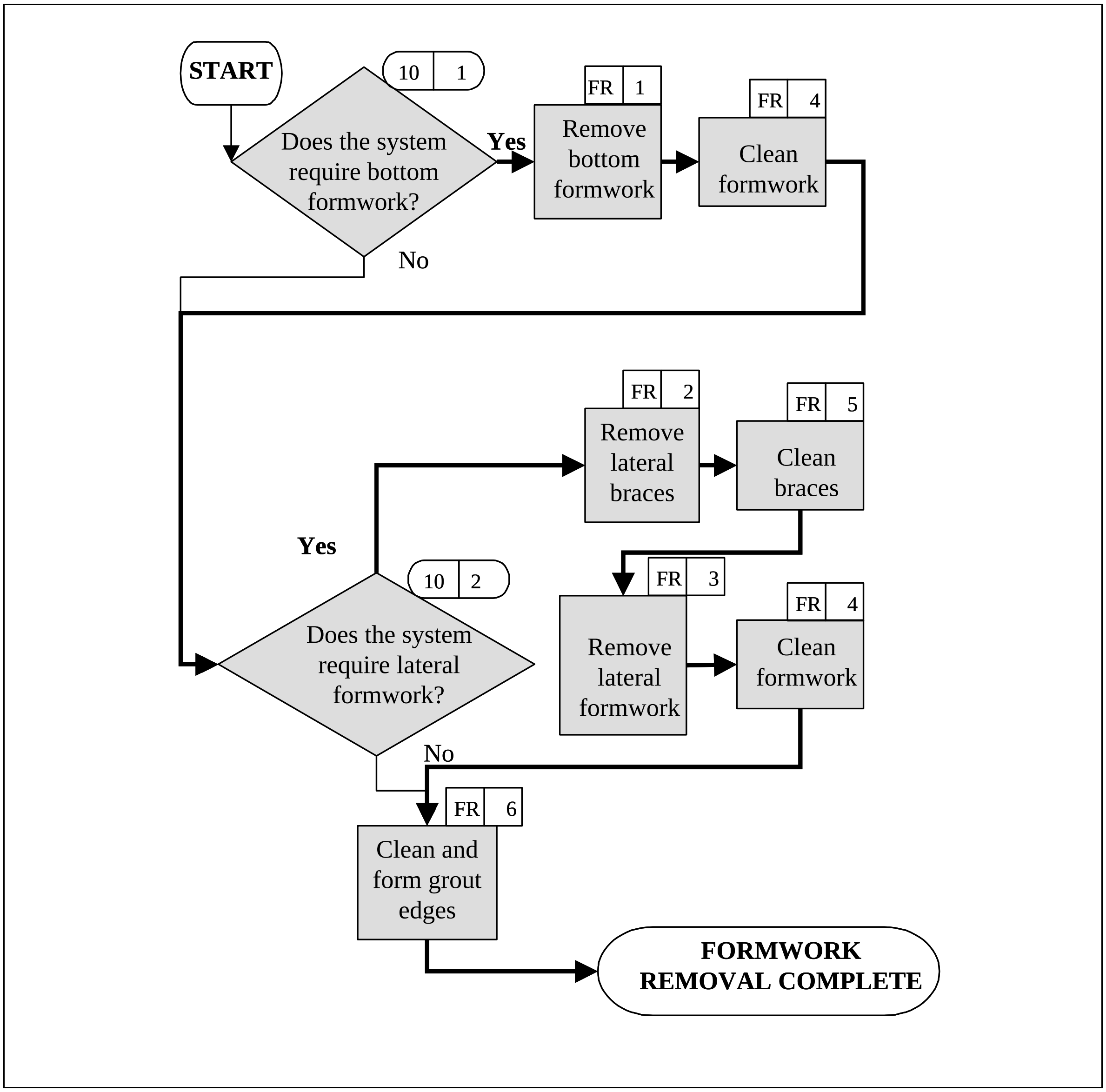

Figure 5.17 Flowchart Used by the Formwork Removal Module

5.4 Construction Process Model Structure

The data used in the Construction Process Model were modeled using the entity-relationship model. Table 5.2 defines the functional needs of the entities used by the model by discussing why such entities are needed.

Table 5.2 Functional Needs of Entities Used by the Construction Process Model

Goal	Entity	Discussion
Define construction tasks	"task"	This entity provided a definition and a tool to identify all construction tasks stored in the model so that they did not have to be re-defined by the user every time those construction tasks were required for the repair of a specific element.
Define construction subtasks	"subtask"	Each construction task could be further divided into construction subtasks. This entity provided a definition and a tool to identify all construction subtasks stored in the model, so that they did not have to be re-defined by the user.
Identify the estimate	"estimate"	The model could store several quantity estimates for the same bridge element.
Uniquely identify the bridge element being repaired with a single identifier	"estimate_element"	To link the model to Pontis™, bridge elements in the Damage Assessment Model were identified using the same group of key attributes used by Pontis™. However, to reduce the amount of unnecessary data manipulated by the model, this entity linked such group of Pontis™ key attributes to a single identification number for a given estimate.
Store construction tasks that were assigned to a given element within an estimate	"estimate_task"	The model needed to store the construction tasks and subtasks that were selected by the construction process flowcharts for a given element and estimate.
Group construction tasks in modules	"module"	The user might need to know which construction tasks were repeated or joint tasks. The modularity of the model might facilitate the implementation of a software system later.

5.4.1 The“Task” and “Subtask” Entities

These entities were used to define all construction tasks and construction subtasks considered in the model. The “task” and “subtask” entities are shown in Figures 5.18 and 5.19 respectively. Attributes shown underlined are “key” attributes. Attributes shown in bold are Pontis™ attributes. A description of the attributes on the “task” entity is given below.

- *taskID* – (Key attribute) – Identified a construction task.
- *taskdef* – Defined a construction task.

The “subtask”entity was composed of the following attributes:

- *taskID* – (Key attribute) – Defined previously.
- *subtaskID* – (Key attribute) – Identified a construction subtask.
- *subtaskdef* – Defined a construction subtask.

Sample data contained in the “task” and “subtask” entities are shown in Table 5.3 and Table 5.4.

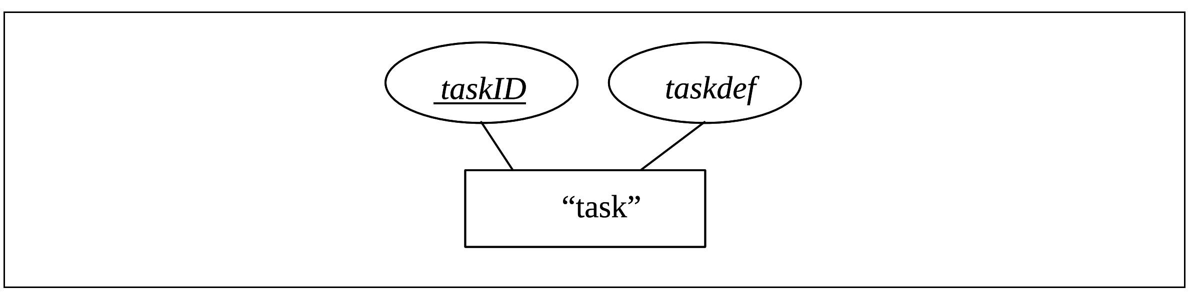

Figure 5.18 The “Task” Entity and its Attributes

Table 5.3 Sample Data Contained in the "Task" Entity

<u>taskID</u>	*taskdef*
CR	Concrete removal
PB	Protective barriers use
RR	Reinforcement repair
FP	Formwork placement

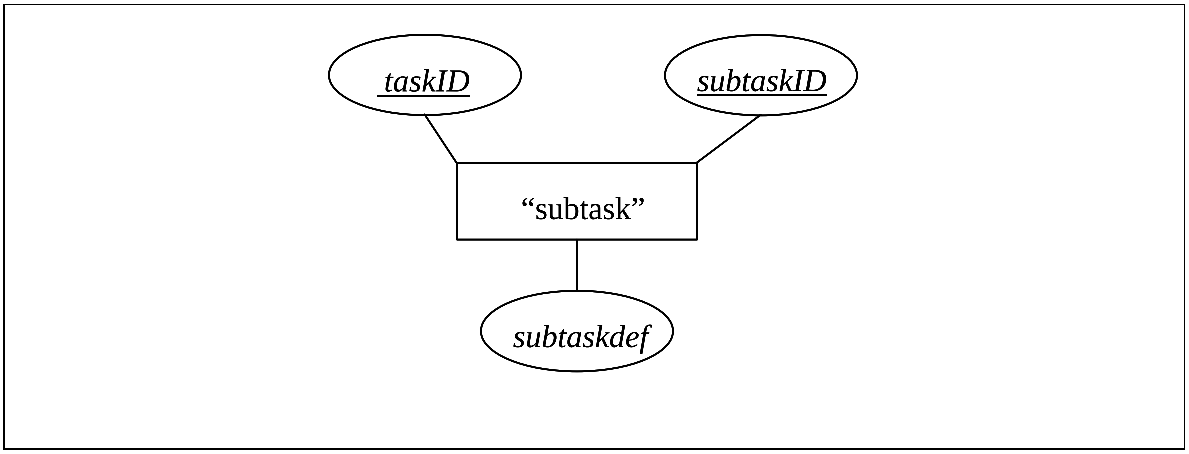

Figure 5.19 The "Subtask" Entity and its Attributes

Table 5.4 Sample Data Contained in the "Subtask" Entity

<u>taskID</u>	*<u>subtaskID</u>*	*taskID*
CR	1	Remove existing jacket
CR	2	Remove existing anode
CR	3	Sound test concrete area
CR	4	Remove large pieces of unsound concrete
PB	1	Place floating protective barriers
PB	2	Remove floating protective barriers

5.4.2 The "Estimate" Entity

This entity uniquely identified a quantity estimate. The model could store several quantity estimates since a bridge could be repaired several times or the engineer might need to compare quantity estimates for different repair methods. The "estimate" entity is shown in Figure 5.20.

The "estimate" entity was composed of the following attributes:

- <u>*estimateID*</u>– (Key attribute) – Identified an estimate.
- *est_date* – Listed the date when the estimate was created.
- *description* – Allowed the user to provide a short description of the estimate.

Sample data contained in the "estimate" entity is shown in Table 5.5.

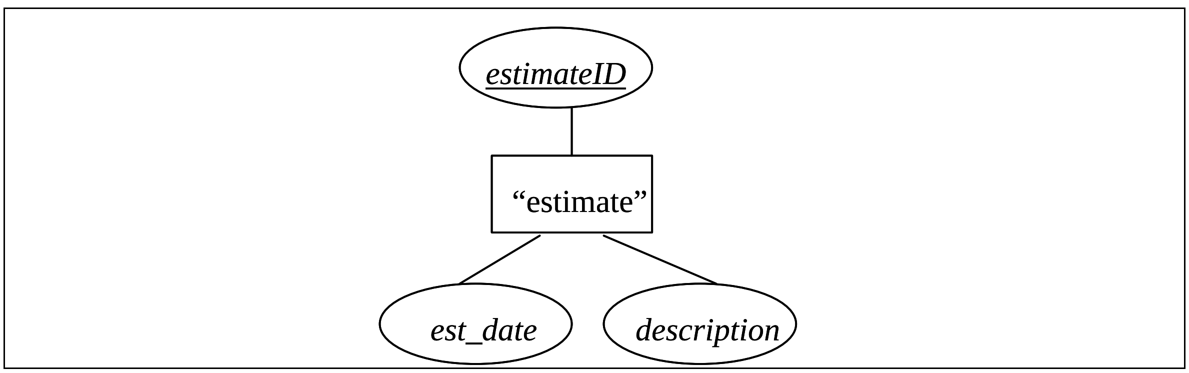

Figure 5.20 The "Estimate" Entity and its Attributes

Table 5.5 Sample Data Contained in the "Estimate" Entity

estimateID	*est_date*	*description*
1	1/10/2004	Install integral CP jackets with sacrificial anode mesh on bridge piles.
2	1/12/2004	Provide exterior post-tensioned reinforcement to pile.
3	1/15/2004	Provide additional steel mesh to pile.
4	1/16/2004	Remove existing jacket.

5.4.3 The "Estimate_Element" Entity

The purpose of this entity was to identify the element being repaired. In Pontis™ each element was identified using several key attributes. The "estimate_element" entity, shown in Figure 5.21, linked various attributes to a single attribute, which was unique, thus reducing the amount of data that was manipulated while creating an estimate. Sample data contained in the "estimate_element"entity is shown in Table 5.6.

The "estimate_element" entity was composed of the following attributes:

- *est-elemID*– (Key attribute) – Uniquely identified an element within an estimate.
- *estimateID* – Identified an estimate.
- ***brkey*** **–** (Pontis™ attribute) - Provided the bridge number to which the quantity estimate referred.
- ***spankey*** **–** (Pontis™ attribute) – Listed the bridge span were the element was located.
- ***elemkey*** **–** (Pontis™ attribute) – Bridge element type, as defined in Pontis™.
- *elemID* **–** Uniquely identified an element within a span in the bridge.

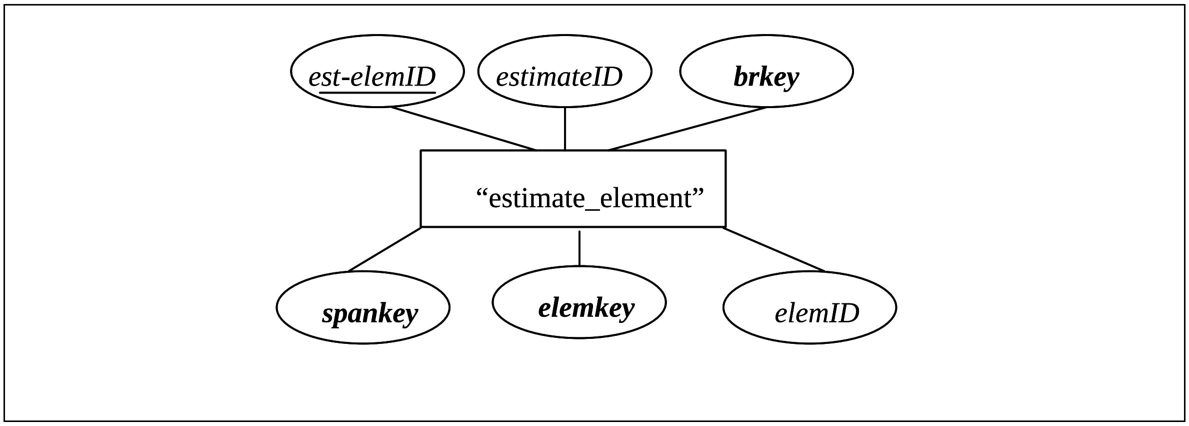

Figure 5.21 The "Estimate_Element" Entity and its Attributes

Table 5.6 Sample Data Contained in the "Estimate_Element" Entity

est-elemID	*estimateID*	***brkey***	***elemkey***	***spankey***	*elemID*
1	1	150107	226	6	6
2	1	150107	226	12	8
3	1	150107	226	13	3
4	2	150107	226	6	6
5	3	150107	226	6	6
6	4	720076	227	46	1

5.4.4 The "Module" Entity

As discussed earlier, the Construction Process Model was composed of modules that grouped related construction task. The "module" entity, shown in Figure 5.22, allowed the model to identify activities that were included in the same module. Sample data contained in the "module" entity is shown in Table 5.7.

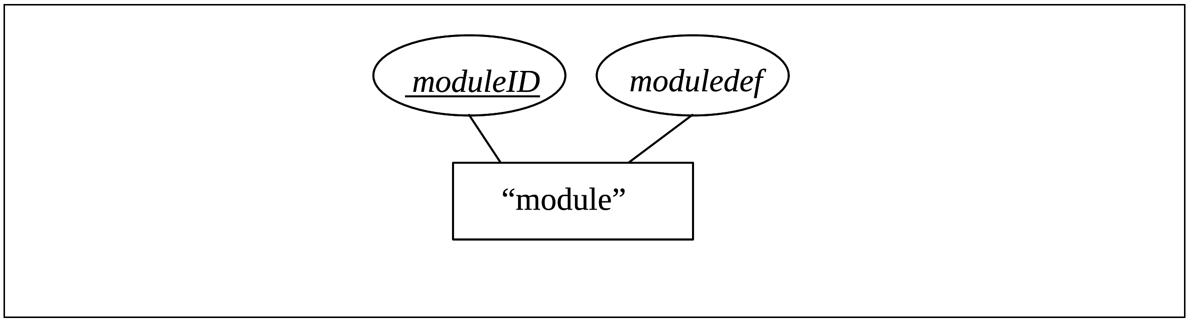

Figure 5.22 The "Module" Entity and its Attributes

Table 5.7 Sample Data Contained in the "Module" Entity

moduleID	*moduledef*
1	Module selection
2	Pile access
3	Concrete removal
4	Reinforcement repair
5	Continuity bonding
6	Formwork placement
7	Jacket placement
8	Grout casting
9	Grout mobilization
10	Formwork removal
11	Continuity testing
12	Reference cell installation

5.4.5 The “Estimate_Task” Entity

This entity stored the construction tasks and subtasks required to repair each element that was considered in a given estimate. The “estimate_task”is shown in Figure 5.23.

The entity “estimate_task” had the following attributes:

- *est-taskID* – (Key attribute) Identified a construction task assigned to an element for a given estimate.
- *est-elemID* – Identified the element being repaired.
- *moduleID*– Identified the module that selected the construction task.
- *taskID* – Identified the construction task assigned to the element being repaired.
- *subtaskID* – Identified the construction subtask assigned to the element being repaired.

Sample data contained in the “estimate_task” entity is shown in Table 5.8. The sample data shown corresponded to construction tasks and subtasks selected by the pile access module, the concrete removal module and the reference cell installation module for the example pile (pile 6 span 6 of bridge 150107). Table F.1 in Appendix F lists all the construction tasks that were selected for the example pile.

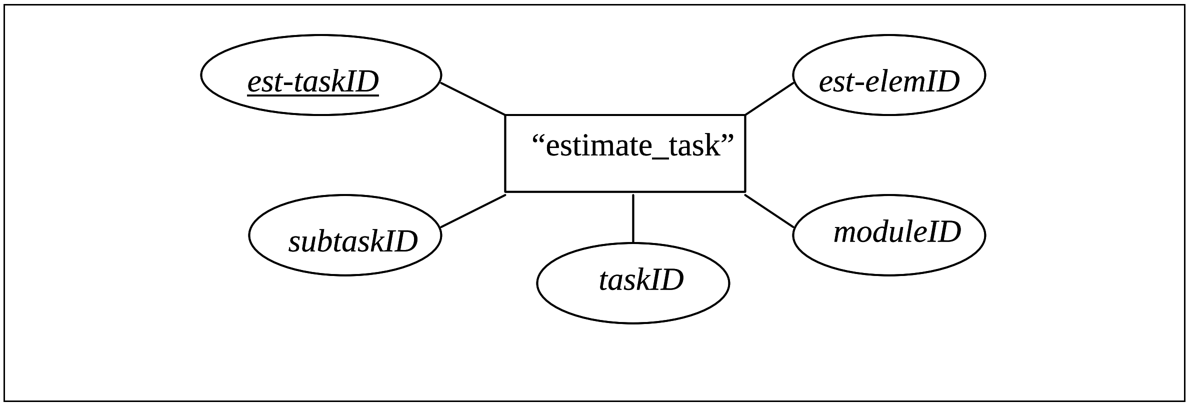

Figure 5.23 The "Estimate_Task" and its Attributes

Table 5.8 Sample Data Contained in the "Estimate_Task" Entity

est-taskID	*est-elemID*	*moduleID*	*taskID*	*subtaskID*
1	1	1	PB	1
2	1	1	PA	5
3	1	2	CR	3
4	1	2	CR	4
5	1	2	CR	5

5.5 Example Query

To illustrate the type of data that could be stored and retrieved from the Construction Process Model, the author created an example query described in Example 5.5.1.

Example 5.5.1. Construction Tasks Required to Repair a Specific Bridge Element

The data retrieved by the query were modeled using the "estimate_task", "estimate_element", "estimate", "subtask", "task" and "module" entities from the Construction Process Model and the "element" and "elementdef" entities from the

Damage Assessment Model (see Chapter IV). The purpose of Example 5.5.1 was to generate a report that listed all construction tasks required to repair a specific element. The report is shown in Figures 5.24 and 5.25. The construction tasks shown in the report were those shown highlighted in the construction process flowcharts, which correspond to the example pile used throughout Chapter IV and V (pile 6 span 6 of bridge 150107).

The author entered the data manually into a Microsoft® Access (2000) sample database. The data were retrieved from the database using a SQL code included in Appendix F. The results of the query and the Microsoft® Access (2000) Wizard used to generate the report from the query was also included in Appendix F, as well as all tables and data used in the query. The construction tasks listed in the report were not part of the current Pontis™ database but were linked to the bridge element using Pontis™ attributes (bridge number, span number and element type). The fact that this report could be generated from data stored in the Construction Process Model proved that detailed construction data could be maintained in an electronic format compatible with the Pontis™ database.

CONSTRUCTION TASKS REQUIRED TO REPAIR A SPECIFIC BRIDGE ELEMENT

Estimate Description: Install integral cathodic protection jackets with sacrificial anode mesh on bridge piles

Bridge No.: 150107
Estimate No.: 1
Estimate Date: 1/10/2004
Bridge Element: Prestressed concrete pile 6 on span 6
Pontis condition State : 4

MODULE	CONSTRUCTION TASK DESCRIPTION
PILE ACCESS	Place floating protective barriers
PILE ACCESS	Access submerged pile using a platform
CONCRETE REMOVAL	Sound test concrete area
CONCRETE REMOVAL	Remove large pieces of unsound concrete
CONCRETE REMOVAL	Remove loose particles and remaining unsound concrete
REINFORCEMENT REPAIR	Clean reinforcement
REINFORCEMENT REPAIR	Form rebar cage
REINFORCEMENT REPAIR	Place rebar cage around pile
REINFORCEMENT REPAIR	Connect continuity wires between existing and new reinforcement
REINFORCEMENT REPAIR	Clean pile surface
CONTINUITY TESTING	Locate reinforcement position
CONTINUITY TESTING	Drill holes on concrete pile to expose reinforcement
CONTINUITY TESTING	Select base reinforcement
CONTINUITY TESTING	Measure potential difference between base reinforcement and others
CONTINUITY TESTING	Patch holes drilled in the concrete pile
CONTINUITY BONDING	Locate area of concrete to be removed
CONTINUITY BONDING	Saw cut concrete to make a small excavation
CONTINUITY BONDING	Remove concrete to make a small excavation
CONTINUITY BONDING	Weld negative connection to transverse reinforcement
CONTINUITY BONDING	Cover welds with epoxy
CONTINUITY BONDING	Restore small excavations on pile surface to original profile
CONTINUITY BONDING	Connect continuity wires between existing pile reinforcement

Page 1 of 2

Figure 5.24 Report Generated Using Data Stored in the Construction Process Model, Page 1

MODULE	CONSTRUCTION TASK DESCRIPTION
REFERENCE CELL INSTALLATION	Test reference cell
REFERENCE CELL INSTALLATION	Locate area of concrete to be removed
REFERENCE CELL INSTALLATION	Remove concrete to make a small excavation
REFERENCE CELL INSTALLATION	Install reference cell
REFERENCE CELL INSTALLATION	Restore small excavations on pile surface to original profile
FORMWORK PLACEMENT	Move formwork to working place
FORMWORK PLACEMENT	Measure bottom formwork position
FORMWORK PLACEMENT	Install bottom formwork
JACKET PLACEMENT	Mobilize jackets to bridge site
JACKET PLACEMENT	Move jacket to working place
JACKET PLACEMENT	Place jacket at proper elevation
JACKET PLACEMENT	Apply epoxy to jacket seams
JACKET PLACEMENT	Snap jackets together
JACKET PLACEMENT	Insert jacket fasteners
FORMWORK PLACEMENT	Install lateral formwork
FORMWORK PLACEMENT	Install lateral braces
GROUT MOBILIZATION	Mobilize grout truck to bridge site
GROUT MOBILIZATION	Mobilize grout pump to bridge site
GROUT MOBILIZATION	Quality control: slump test
GROUT MOBILIZATION	Quality control: strength cylinder casting
GROUT MOBILIZATION	Place grout hose at the bottom of the jacket
GROUT CASTING	Pump grout trough a hose
GROUT CASTING	Remove grout hose
GROUT CASTING	Grout cast in jacket curing time
GROUT CASTING	Clean grout waste
FORMWORK REMOVAL	Remove bottom formwork
FORMWORK REMOVAL	Clean formwork
FORMWORK REMOVAL	Remove lateral braces
FORMWORK REMOVAL	Clean braces
FORMWORK REMOVAL	Remove lateral formwork
FORMWORK REMOVAL	Clean formwork
FORMWORK REMOVAL	Clean and form grout edges

Page 2 of 2

Figure 5.25 Report Generated Using Data Stored in the Construction Process Model, Page 2

5.6 <u>Conclusions</u>

The Construction Process Model was used to incorporate the logic behind the construction process for different repair methods and for different Pontis™ bridge elements using repair matrices and flowcharts. Seven repair matrices were developed to define specific repair methods for each one of the bridge elements considered in the Pontis™ database. Flowcharts were developed for the Pontis™ concrete pile elements and the repair methods included in the scope of this research. The flowcharts were composed of construction tasks arranged in sequential order and decision points. The model inferred the answers for the decision points in the flowcharts from knowledge rules that combined specific site conditions, damage existing in the element and input parameters. A construction process was defined based on the answers inferred for the decision points, which resulted in the selection of specific construction tasks for the bridge element under consideration.

In Pontis™, each element in a given condition state had at most three MR&R options. For concrete pile elements in Pontis™ Condition State 1, 2, 3, or 4 options were “replacement”, “repair” or “do nothing”. Such definitions did not specify the repair method, the existing damage in the element or site conditions. In contrast, Chapter V demonstrated a methodology to select construction tasks for a specific pile based on the repair method, the existing damage in the pile and the site conditions.

Data describing construction tasks considered, as well as construction tasks assigned to a specific element for a specific estimate, were modeled using entities. Entities were modeled so that they could be applied to different bridge elements and repair methods in a format compatible with the existing Pontis™ database.

Modeling the logic behind repair methods by incorporating repair guidelines, heuristics, construction processes, specific site conditions, expert knowledge and the Pontis™ database is an innovation in construction engineering that can be used as a MLE quantity estimating tool to define construction tasks at the pre-design stage.

CHAPTER VI

PARAMETRIC QUANTITY MODEL

6.1 Introduction

This chapter provides a methodology to define MLE quantities at the pre-design stage that take into consideration the physical and site condition of the bridge. Specific research objectives accomplished in this chapter are: (1) estimate MLE quantities for the construction tasks selected by the damage assessment model, and (10) review and assess the existing, federally owned PACES bridge models and develop specific engineering algorithms to augment the PACES bridge models. These objectives are related to the research methodology section highlighted in Figure 6.1

The Parametric Quantity Model combined data generated by the Damage Assessment Model and the Construction Processes Model with additional expert knowledge to calculate quantities. Similar to the methodology used in PACES, the Parametric Quantity Model incorporated required and secondary parameters into equations to estimate quantities. The user input required parameters while secondary parameters could either be calculated or default values selected. Using default values as secondary parameters reduced the amount of data input by the user. The default values were the values that occurred most often (the statistical “mode”) on data collected by the author from previous FDOT repair projects.

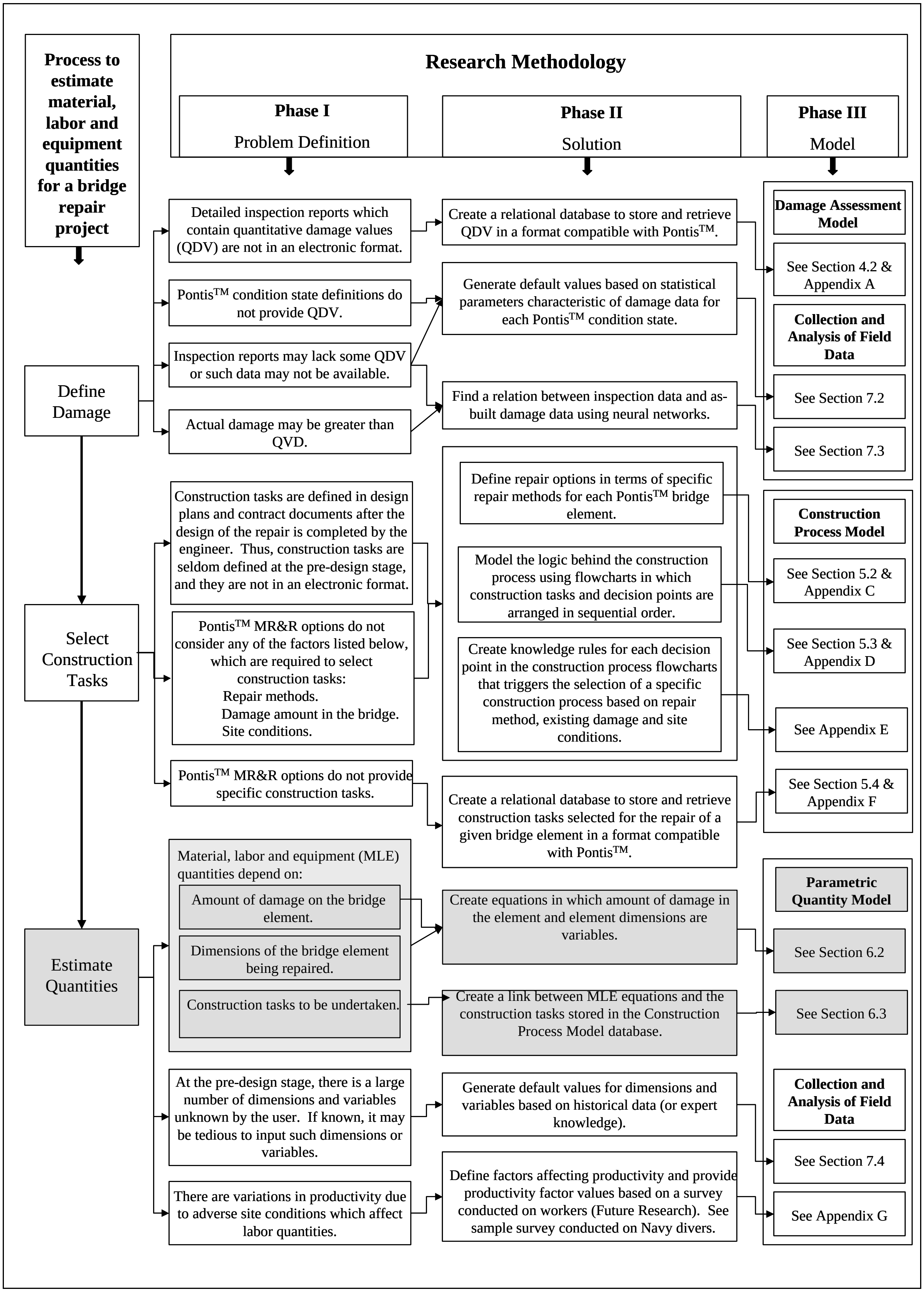

Figure 6.1 Research Methodology

PACES contained models for construction of new simple span bridges, but PACES did not include models for repair projects. In PACES methodology, most of the input parameters were constant within the same project, minimizing the amount of input parameters. As an example, considering the construction of a new bridge, the dimensions of the piles most likely was constant throughout the bridge construction. As a result, few parameters were required to estimate bridge pile quantities, and PACES did not need to have the capability of handling different values for the same type of pile dimension within the same estimate.

In the case of bridge repair, there might be hundreds of values for the input parameters required to define the damage in the bridge, which might result in the selection of different construction tasks for each one of the bridge piles considered within the same MLE quantity estimate.

The new methodology had the capability to handle different values for the same input parameter by storing such values in the Damage Assessment Model and retrieving them as input parameters as required by the Construction Process Model.

6.2 Parametric Quantity Model Structure

Each construction task defined in the Construction Process Model was linked to one or more quantity item defined in the Parametric Quantity Model. For each quantity item there was a set of equations and knowledge rules used to estimate the MLE quantities. In the Parametric Quantity Model there was not distinction made to classify quantities as either a material, labor or an equipment quantity.

Quantity items were modeled using the entity-relationship model. The quantity item entity (“qty_item”) was used to identify and define the quantity items that should be considered for each construction task-subtask combination considered in the Construction Process Model.

For a single construction task-construction subtask combination, there could several quantity items. Thus, the relationship between the construction subtask entity ("subtask") and the quantity items entity and was a "one-to-many" relationship (1 : N). Such a relationship provided a tool to link the Construction Process Model to the Parametric Quantity Model. The construction subtask entity in turn, was linked to the entity used to store the construction tasks assigned to a specific element for a given estimate ("estimate_task") and the construction task entity ("task") as shown in Figure 6.2.

The quantity item entity did not refer to a specific pile or estimate. Rather it referred to construction subtasks in general. The quantity items for a specific pile on a given estimate were determined using an SQL query which combined and retrieved data from the "estimate_task" entity and the quantity item entity as shown later in Example 6.3.1

The quantity item entity, shown in Figure 6.3, had the following attributes:

- <u>*qtyitemID*</u> – Key attribute used to identify the quantity item.
- *qtyitemdef* – Attribute used to define the material quantity item.
- *taskID* –Attribute used to identify the construction task.
- *subtaskID* – Attribute used to identify the construction subtask.

Table 6.1 lists sample data contained in the quantity item entity. In Table 6.1, there were quantity items which were selected by the query discussed in Example 6.3.1 (shown highlighted), as well as others not considered. Table 6.1 contains a module definition column (*moduledef*), which was not part of the "qty_item" entity. The module definition column was included in the table to facilitate the identification of the construction tasks by the reader, otherwise the construction task and subtask identification numbers might had been meaningless to the reader. In addition, the construction task and subtask definitions as well as the module definitions were already stored in the model in the "task", "subtask" and "module" entities, and they should not be duplicated. Such definitions could be easily retrieved using an SQL query.

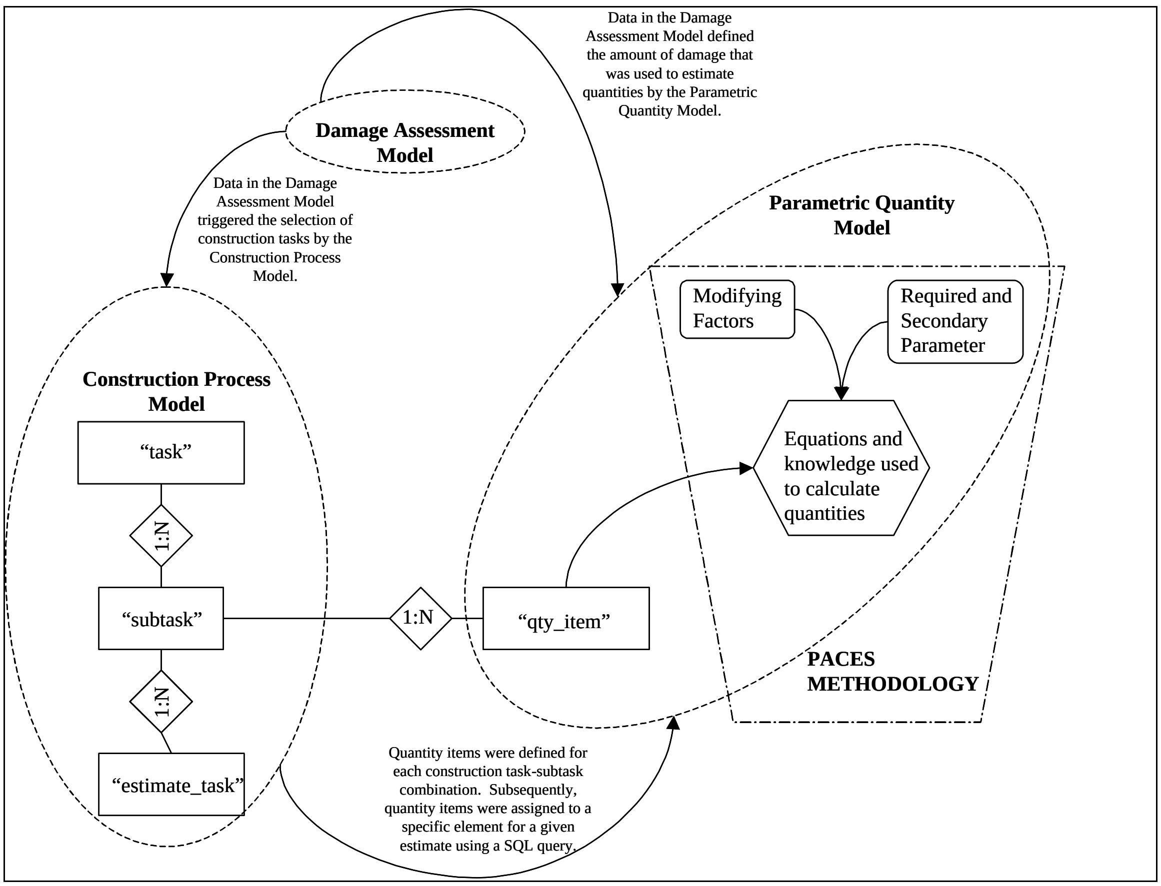

Figure 6.2 View of the Parametric Quantity Model and its Similarities to PACES

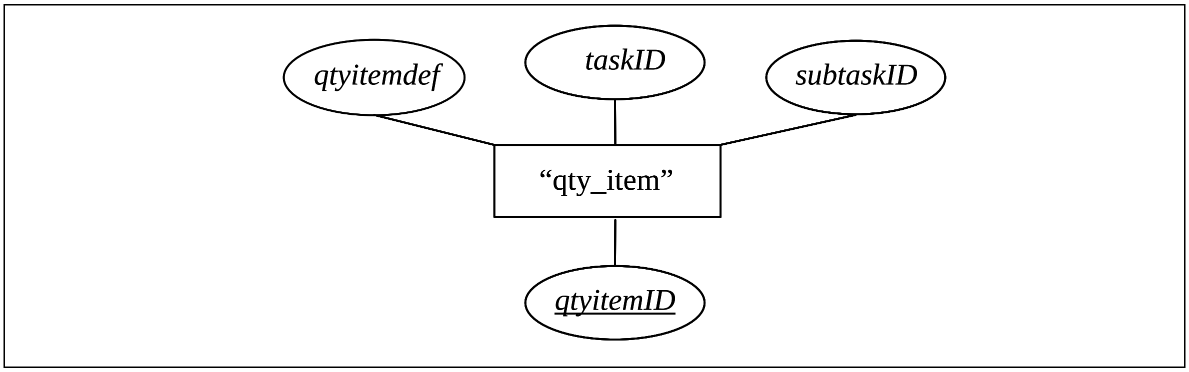

Figure 6.3 The Quantity Item Entity ("Qty_Item") and its Attributes

Table 6.1 Sample Data Contained in the Quantity Item Entity

qtyitemID	*qtyitemdef*	*taskID*	*subtaskID*	*moduledef*
1	Concrete cutting	CR	8	Continuity Bonding
2	Continuity excavation	CR	9	Continuity Bonding
3	Connection	CB	4	Continuity Bonding
4	Continuity wire	CB	4	Continuity Bonding
5	Continuity wire weld	CB	4	Continuity Bonding
6	Negative connection wire	CB	3	Continuity Bonding
7	Epoxy volume	CP	2	Continuity Bonding
8	Grout volume	CP	3	Continuity Bonding
9	Jacket	JP	1	Jacket Placement
10	Standoff	JP	1	Jacket Placement
11	Longitudinal seam epoxy	JP	4	Jacket Placement
12	Transverse seam epoxy	JP	4	Jacket Placement
13	Jacket fasteners	JP	6	Jacket Placement
14	Jacket fabrication	JP	1	Jacket Placement
15	Excavate dry soil	EX	1	Formwork Placement
16	Excavate wet soil	FP	3	Formwork Placement

6.3 Example Query and Example Cost Estimating

The query discussed in Example 6.3.1 retrieved the quantity items that should be considered for the repair of a specific pile for a given estimate. In Example 6.3.2, quantities and costs for jacket placement quantities were calculated.

Example 6.3.1 -Quantity Items for a Specific Pile for a Given Estimate

To illustrate the methodology, the same concrete bridge pile used as an example in the previous chapters was also considered in Example 6.3.1 (pile 6 span 6 bridge 150107). Only the quantity items required for the construction tasks selected in the Jacket Placement Module and the Continuity Bonding Module for the example pile were considered. The construction tasks related to the quantity items discussed were shown highlighted in Figures 5.11 and 5.14. Quantity items required for all the other construction tasks were not defined by the author and were recommended for future research since the methodology was the same.

Figure 6.4 shows a report generated using the data stored in the quantity item entities and the construction process model. This report provided the bridge identification number, a specific bridge element, the estimate identification number, the Pontis™ Condition State used to classify the element and the quantity items required to repair the element. The SQL command as well as the Microsoft® Access (2000) Wizard used to generate the report are presented in Appendix G. Equations and knowledge used to calculate quantities for each one of the quantities items described were developed and are discussed in Appendix H. Productivity factors affecting the duration of construction activities are discussed in Appendix I.

QUANTITY ITEMS REQUIRED TO REPAIR A SPECIFIC BRIDGE ELEMENT

Estimate Description: Install integral cathodic protection jackets with sacrificial anode mesh on bridge piles

Bridge No.: 150107

Estimate No.: 1

Estimate Date: 1/10/2004

Bridge Element: Prestressed concrete pile 6 on span 6

Pontis condition State : 4

MODULE	QUANTITY ITEM DESCRIPTION
CONTINUITY BONDING	Concrete cutting
CONTINUITY BONDING	Continuity excavation
CONTINUITY BONDING	Continuity connection
CONTINUITY BONDING	Continuity wire
CONTINUITY BONDING	Continuity wire weld
CONTINUITY BONDING	Negative connection wire
CONTINUITY BONDING	Epoxy volume
CONTINUITY BONDING	Grout volume
JACKET PLACEMENT	Jacket
JACKET PLACEMENT	Standoff
JACKET PLACEMENT	Longitudinal seam epoxy
JACKET PLACEMENT	Transverse seam epoxy
JACKET PLACEMENT	Jacket fasteners
JACKET PLACEMENT	Jacket fabrication

Page 1 of 1

Figure 6.4 Report Created Using the Parametric Quantity Model

Example 6.3.2 – Quantities and Costs for Jacket Placement Quantities

Once the quantity items were defined, the MLE quantities were estimated using the knowledge rules and the equations discussed in Appendix H. Required and secondary parameters for the example discussed are listed in Appendix H, Tables H.1, H.2 and H.4. Expert knowledge provided unit prices for the quantity items under discussion as well as a profit margin (Snow 1999). The mark up margin was calculated as 20 percent of the cost, which was a user defined value. The MLE quantities calculated for the Jacket Placement Module are listed in Table 6.2. Adding all these costs resulted in a cost of $824.75 per jacket.

The cost of the CP system was listed in the design plans under FDOT pay item 2400-142-4 as $450.00 per square meter of jacket and the total jacket quantity was listed as 1,193.7 square meters for the 239 jackets. However, pay item 2400-14-2 included costs associated with continuity testing, continuity correction, jacket placement, grout casting and formwork. According to expert knowledge (Mather 2004), the cost of the CP system excluding continuity testing, continuity correction, grout casting and formwork was approximately 40 percent of the costs listed under pay item 2400-142-4. Thus, the cost per jacket giving by FDOT quantities was defined as follows:

$$\frac{\$450.00 \cdot 1193.7\ \text{m}^2 \cdot 0.40}{239\ \text{Jackets}} = \$899.0\ \text{per jacket}$$

The cost estimated by the model ($824.75) was 8% lower than the costs estimated from the FDOT pay item ($899)

Table 6.2 Costs for Quantities Associated with the Jacket Placement Module

Quantity Item	Unit	Quantity	Unit Cost	Cost per Jacket
Jacket fiberglass	ft^2	58	$6.39	$370.62
Jacket zinc anode mesh	ft^2	58	$4.39	$254.62
Standoff	each	32	$0.10	$3.20
Longitudinal seam epoxy	gallon	0.3	$6.67	$2.01
Transverse seam epoxy	gallon	0.0	$6.67	$0.00
Jacket fasteners	each	36	$0.24	$8.64
Jacket fabrication	lump sum	1	$610.00	$2.60
Labor, senior technician	man-day	14	$450.0	$26.35
Labor, worker	man-day	14	$150.00	$8.79
CP Specialist inspection	lump sum	1	$2,500.00	$10.46
Subtotal:				$687.29
Mark up (20%):				$137.46
Total Cost:				$824.75

6.4 Conclusions

Chapter VI, in conjunction with Appendices G, H and I, provided a description of the Parametric Quantity Model that could be used to define and to estimate quantities to repair bridges at the pre-design stage. Since the Parametric Quantity Model was linked to the Construction Process Model, which in turn was linked to the Damage Assessment Model, the repair quantities items assigned to a specific element were based on construction tasks that were selected by considering the specific site condition of the bridge, the repair method used and the damage existing in the bridge, all of which could be linked to a Pontis™ element on a given Pontis™ Condition State.

CHAPTER VII

COLLECTION AND ANALYSIS OF FIELD DATA

7.1 Introduction

The research objective discussed in this chapter was to provide a methodology to generate default values for parameters used by the model when data were not available. This research objective is related to the research methodology section highlighted in Figure 7.1. The field data analyzed in this section were limited to concrete piles of bridges located in Florida that were under the supervision and management of the FDOT and which showed signs of reinforcement corrosion and concrete deterioration prior to repair. The deterioration data analyzed included inspection reports, project plans and as-built quantities from projects related to the repair of concrete bridge piles. The data were provided by the FDOT District Offices and by the FDOT Corrosion Research Laboratory located in Gainesville, Florida between January 1999 and May 2001.

7.2 Definition of Default Damage Data Values

The deterioration data, corresponding to the different Pontis™ Condition States for concrete piles, showed distinct statistical normal distributions; therefore, it was possible to use statistical descriptors such as the mean and the range of values of the data to characterize damage data corresponding to each Pontis™ Condition State when data were not available from detailed inspection reports.

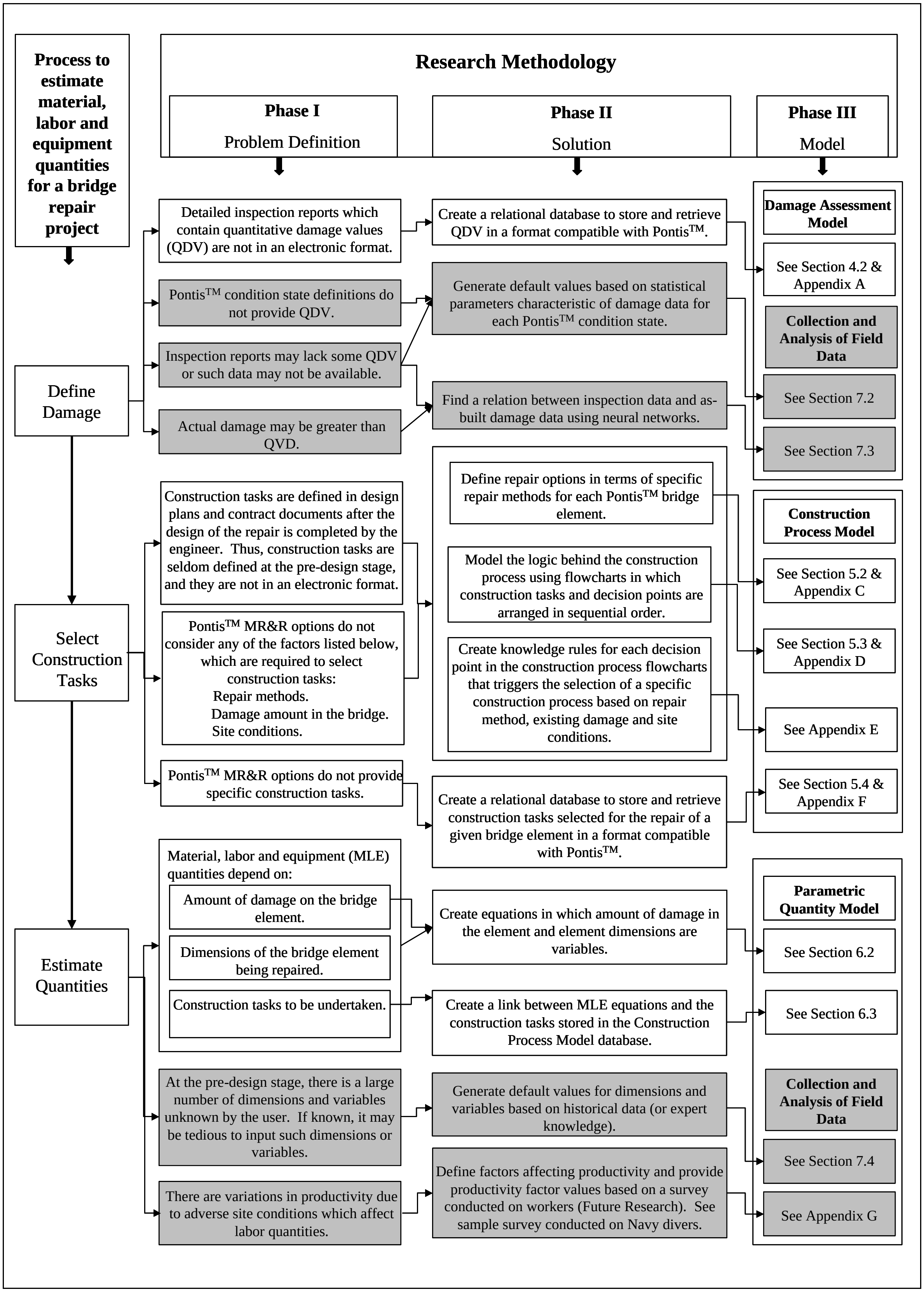

Figure 7.1 Research Methodology

The author calculated these parameters for spall volume and crack length as an example to illustrate the methodology because the data were available and were representative of damage observed in concrete bridge piles. A description of the data used, as well as a discussion of the results of the statistical analysis conducted by the author to define the default values shown in Table 7.1 are included below in Section 7.2.1 through 7.2.4. By definition, there was no damage if the pile was classified in the Pontis™ Condition State 1, thus the table does not include it. The spall data analysis included data above and below the MLW, but the crack length analysis included only data above MLW since it was the only data available. The process is the same for data below water. The reinforcement corrosion data were not included in this section because they were analyzed in Section 7.3.3 and 7.3.4, which related reinforcement corrosion data with concrete deterioration data using neural networks.

7.2.1 Spall Volume Inspection Data for Eleven Bridges

Deterioration data were collected for concrete piles on 11 bridges located throughout Florida. These bridges are listed in Table 7.2.

The spall volume was calculated using the spall dimensions (width, length and depth) as recorded on detailed inspection reports prepared by the FDOT. These data were not available in Pontis™. Inspection reports contained data for 410 spalls. Three hundred and one sets of spall data also contained reinforcement deterioration data used by the author to classify the existing degree of deterioration into Pontis™ Condition States. This latter group of data sets was used to define the distribution of spall volume within each Pontis™ Condition State.

Table 7.1 Default Values for Damage Data Proposed for each Pontis™ Condition State

Parameter	Pontis™ Condition State 2	Pontis™ Condition State 3	Pontis™ Condition State 4
Volume Range of Deteriorated Concrete (cu.ft.) Above Water (MLW)	0.0 - 1.4	0.1 - 3.8	0.2 - 5.8
Mean Volume of Deteriorated Concrete (cu.ft.) Above Water (MLW)	0.1	0.9	1.3
Volume Range of Deteriorated Concrete (cu.ft.) Below Water (MLW)	0.0 - 0.5	0.1 - 3.7	0.4 - 4.6
Mean Volume of Deteriorated Concrete (cu.ft.) Below Water (MLW)	0.1	0.7	1.5
Crack Length (inches) Above Water (MLW)	4.0 - 22.0	5.0 - 39.0	4.0 - 31.0
Mean Crack Length (inches) Above Water (MLW)	10.5	17.5	11.5

Table 7.2 Summary of Bridges Used in the Analysis

Bridge ID	Bridge Name	Facility Carried	Number of Spall Data Sets
150107	Howard Frankland	I-275	92 (Above MLW) 80 (Below MLW)
720076	Mathews	S.R. 10A	23 (Above MLW)
870082	NE 79th St. Causeway (WB)	S.R. 934	9 (Above MLW)
870085	NE 79th St. Causeway (EB)	S.R. 934	5 (Above MLW)
870551	NE 79th St. Causeway (WB)	S.R. 934	3 (Above MLW)
870554	NE 79th St. Causeway (EB)	S.R. 934	8 (Above MLW)
900016	Bahia Honda (SB)	S.R. 5	42 (Above MLW)
900045	Bahia Honda (NB)	S.R. 5	41 (Above MLW)
900095	Indian Key	S.R. 5	9 (Above MLW)
900101	Seven Mile	S.R. 5	171 (Above MLW)
900117	Niles Channel	S.R. 5	10 (Above MLW)

Pontis™ uses the condition state as defined by the *"AASHTO Guide for Commonly Recognized (CoRe) Structural Elements*" (AASHTO 1997). For reinforced concrete column/pile extensions and submerged piles there are four condition states. A definition of each condition state was provided in the Background Chapter, Section 2.3.

7.2.2 Spall Volume Data Analysis

The purpose of the analysis was to determine the distribution of the volume of deteriorated concrete in spalls for each Pontis™ Condition State. The statistical analysis focused on screening the data to identify outliers and to determine if the sample exhibits a normal distribution pattern. This task was done using (1) boxplots and (2) histograms with superimposed normal curves. See the Background Chapter, Section 2.12 (page 45) for a definition of boxplots and histograms. The variable “Volume” was used to represent the volume of deteriorated concrete in a spall and the variable “LOGVOL” to represent the log-transformation of the variable “Volume”.

The boxplots of the variable “Volume” for Pontis™ Condition State 2, 3 and 4 are shown in Figures 7.2 and 7.3 for spalls above MLW and below MLW, respectively. Similarly, the boxplot of the variable “LOGVOL” for Pontis™ Condition State 2, 3 and 4 are shown in Figures 7.4 and 7.5 for spalls above MLW and below MLW respectively. By definition, there were no spalls if the pile was classified in Pontis™ Condition State 1, so Condition State 1 was not included in the graphs. Based on the boxplot graphs, the log-transformed “LOGVOL” variable was used for the analysis since it showed a more symmetric distribution than that of the “Volume” variable. The histograms of the log-transformed variable for each Pontis™ Condition State are shown in Figures 7.6 through 7.11.

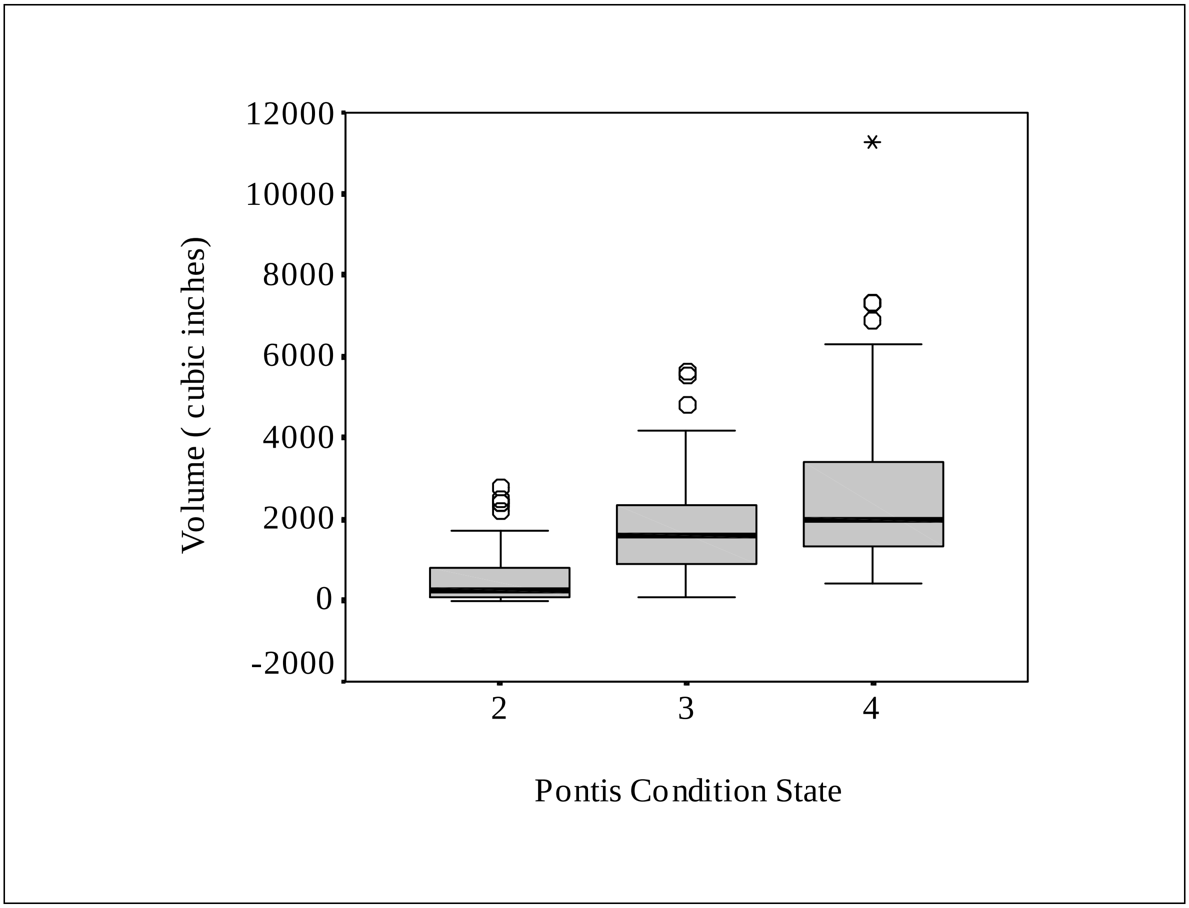

Figure 7.2 Boxplot Graph of the Volume of Deteriorated Concrete on Spalls above MLW (Variable "Volume") for each Pontis™ Condition State

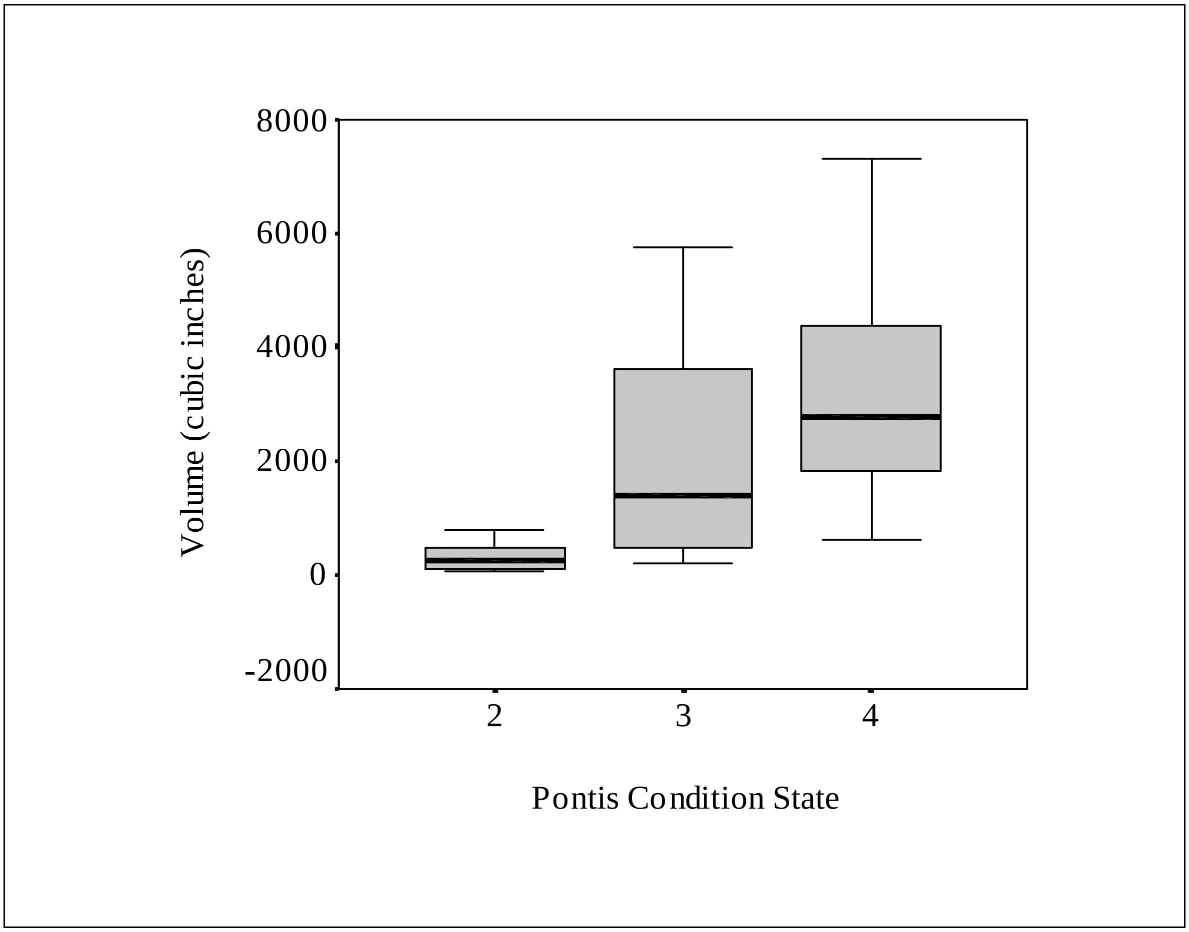

Figure 7.3 Boxplot Graph of the Volume of Deteriorated Concrete on Spalls below MLW (Variable "Volume") for each Pontis™ Condition State

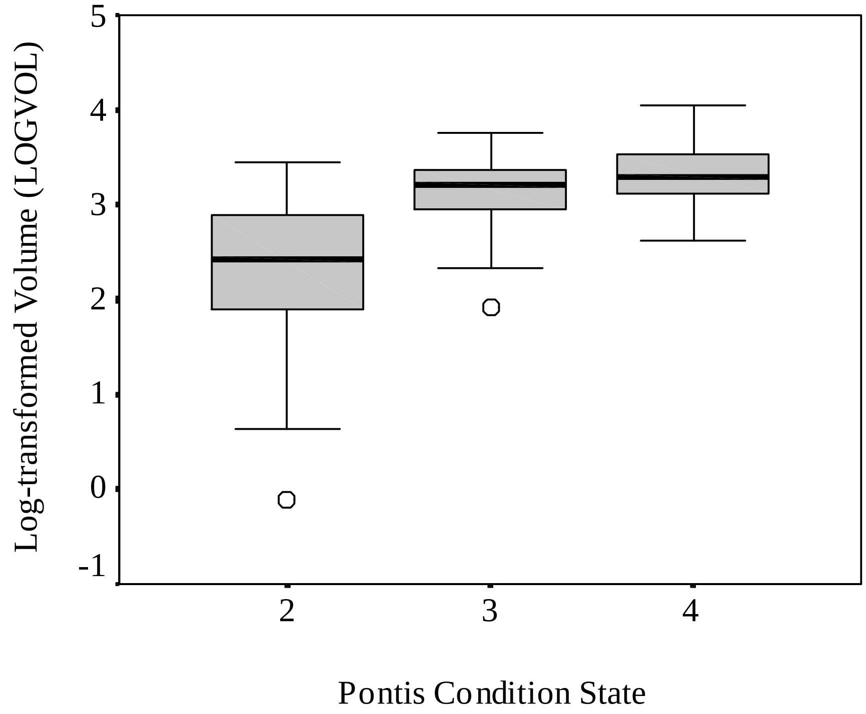

Figure 7.4 Boxplot Graph of the Log-transformed Volume of Deteriorated Concrete on Spalls above MLW (Variable "LOGVOL") for each Pontis™ Condition State

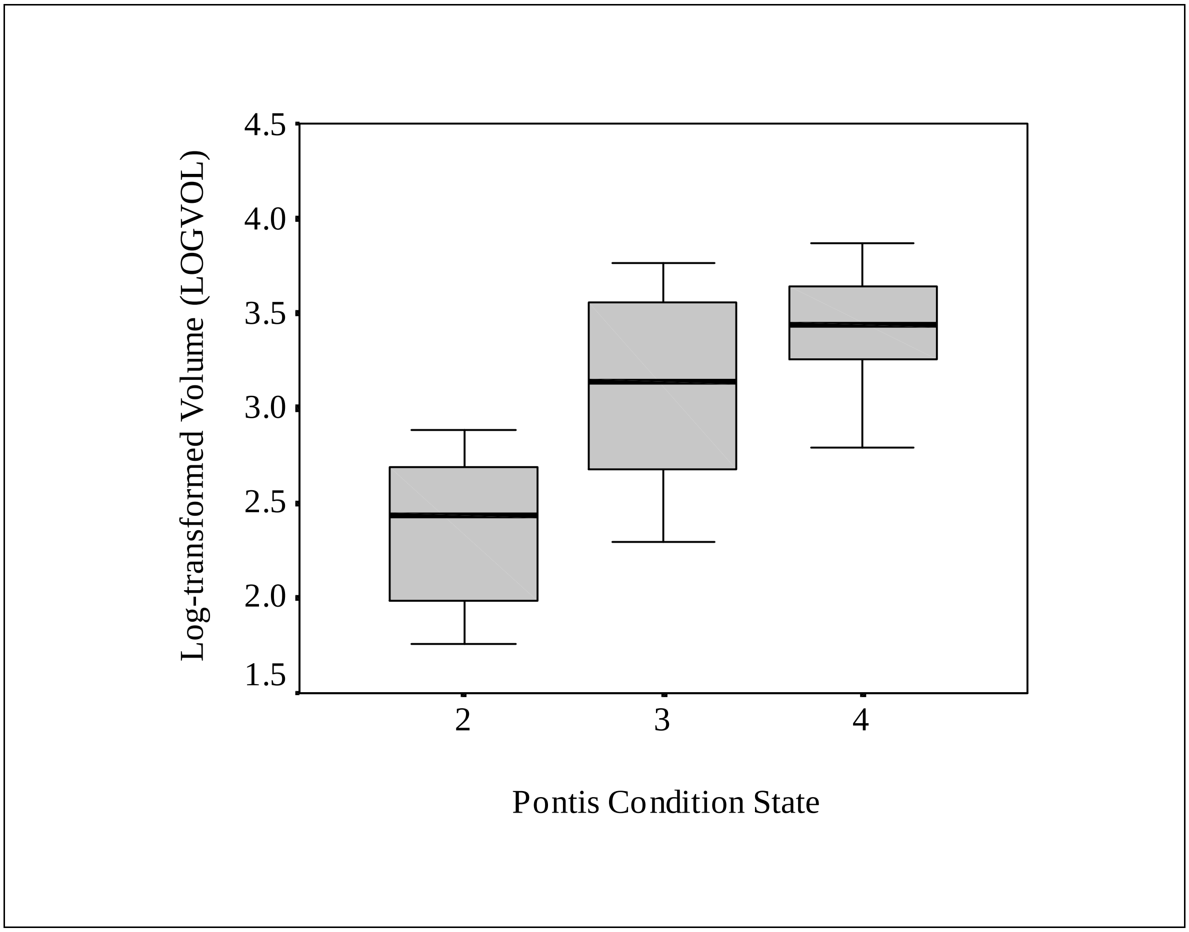

Figure 7.5 Boxplot Graph of the Log-transformed Volume of Deteriorated Concrete on Spalls below MLW (Variable "LOGVOL") for each Pontis™ Condition State

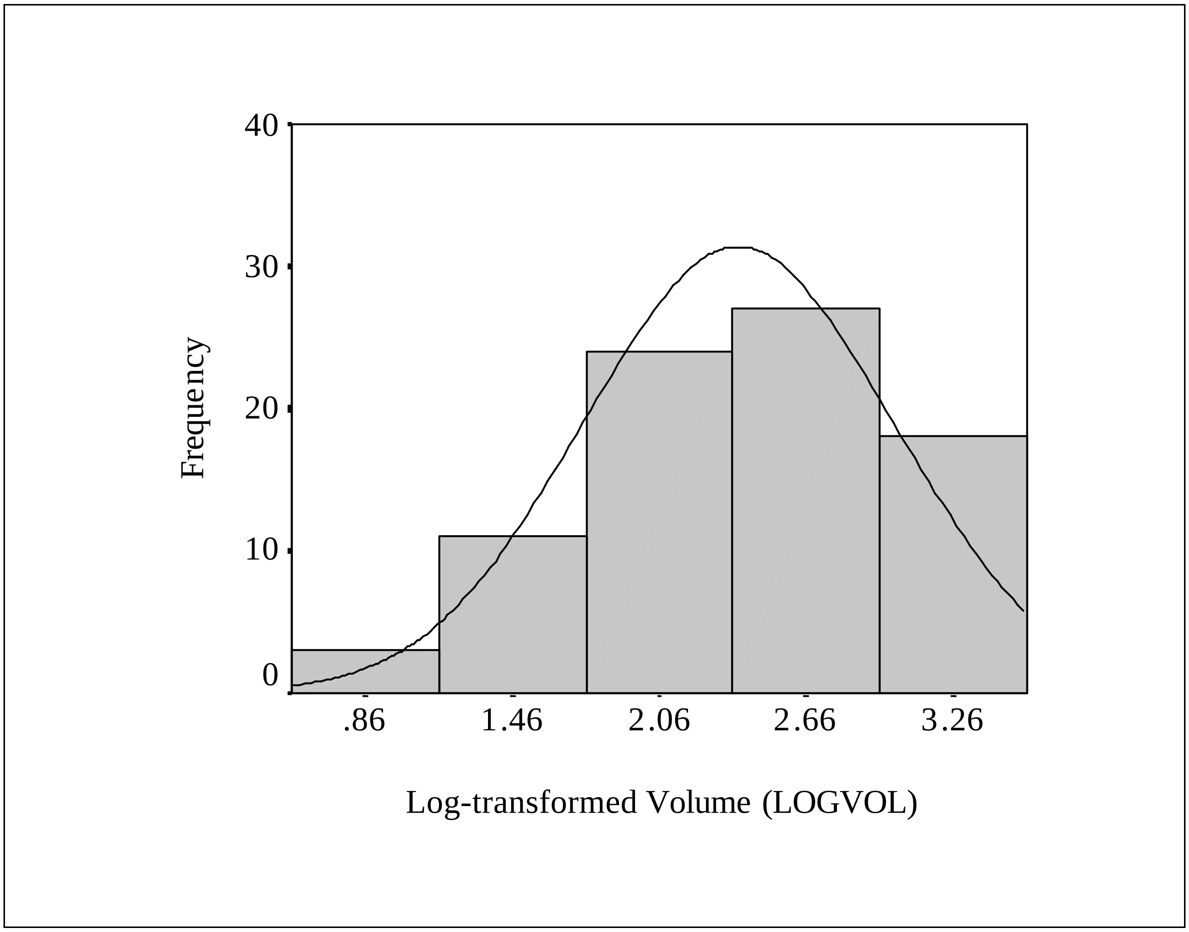

Figure 7.6 Histogram of the Log-transformed Volume of Deteriorated Concrete on Spalls above MLW (Variable "LOGVOL") for Pontis™ Condition State 2

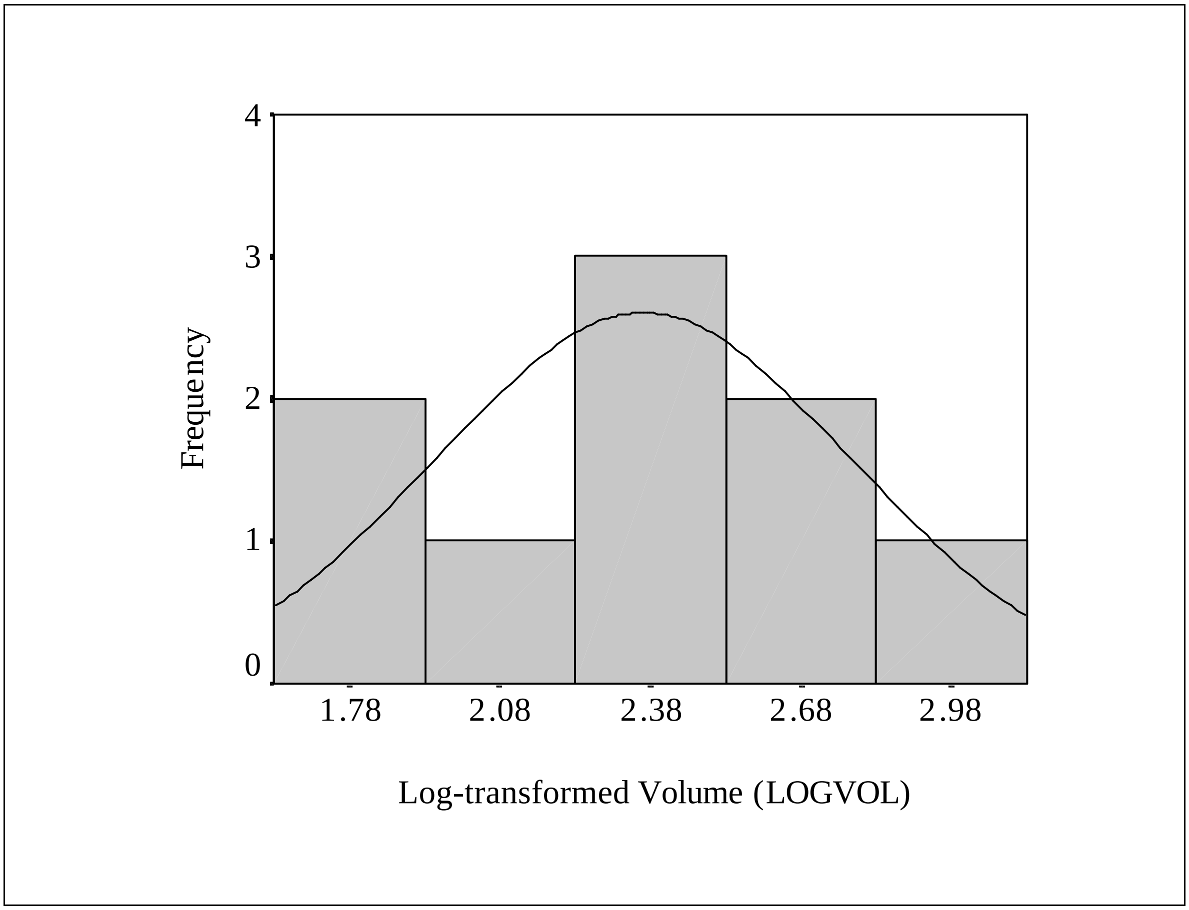

Figure 7.7 Histogram of the Log-transformed Volume of Deteriorated Concrete on Spalls below MLW (Variable "LOGVOL") for Pontis™ Condition State 2

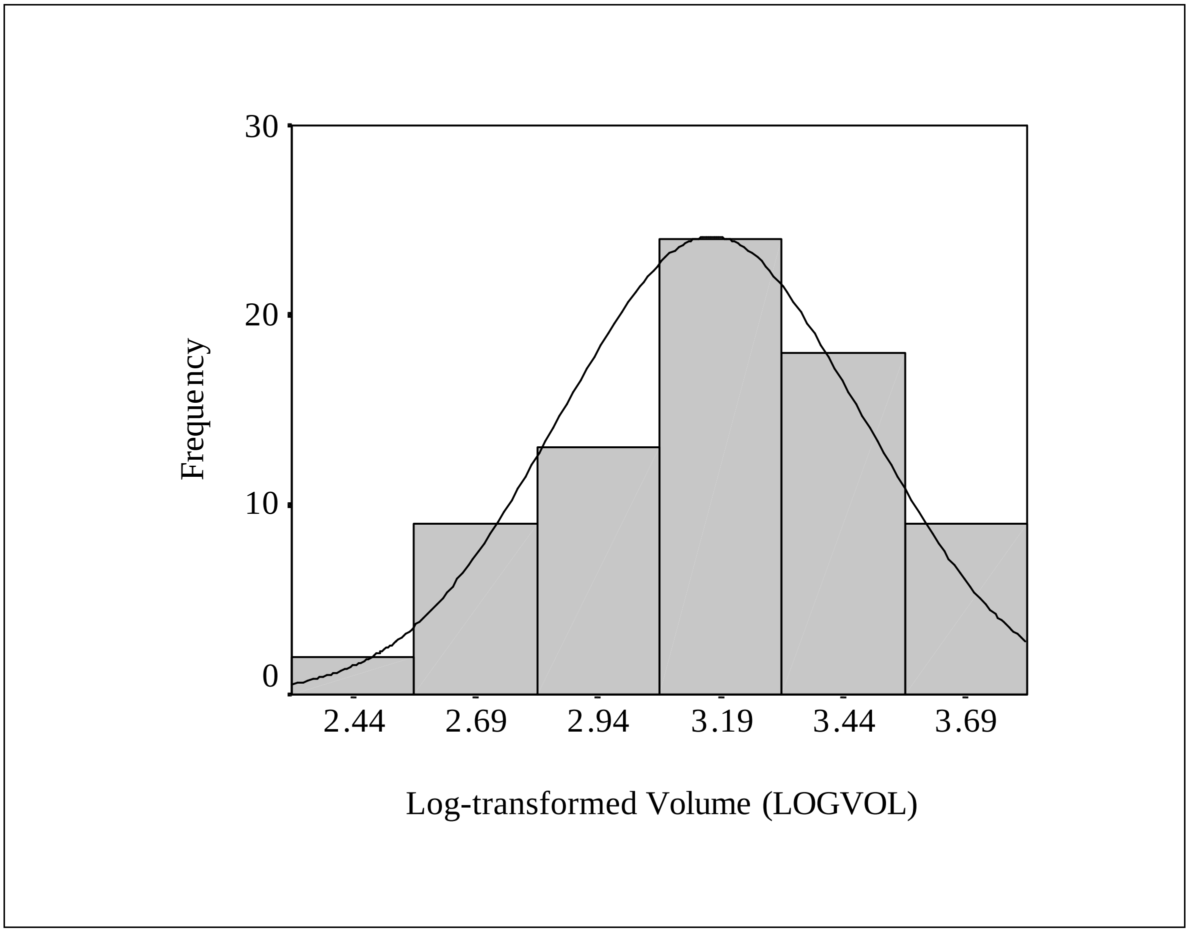

Figure 7.8 Histogram of the Log-transformed Volume of Deteriorated Concrete on Spalls above MLW (Variable "LOGVOL") for Pontis™ Condition State 3

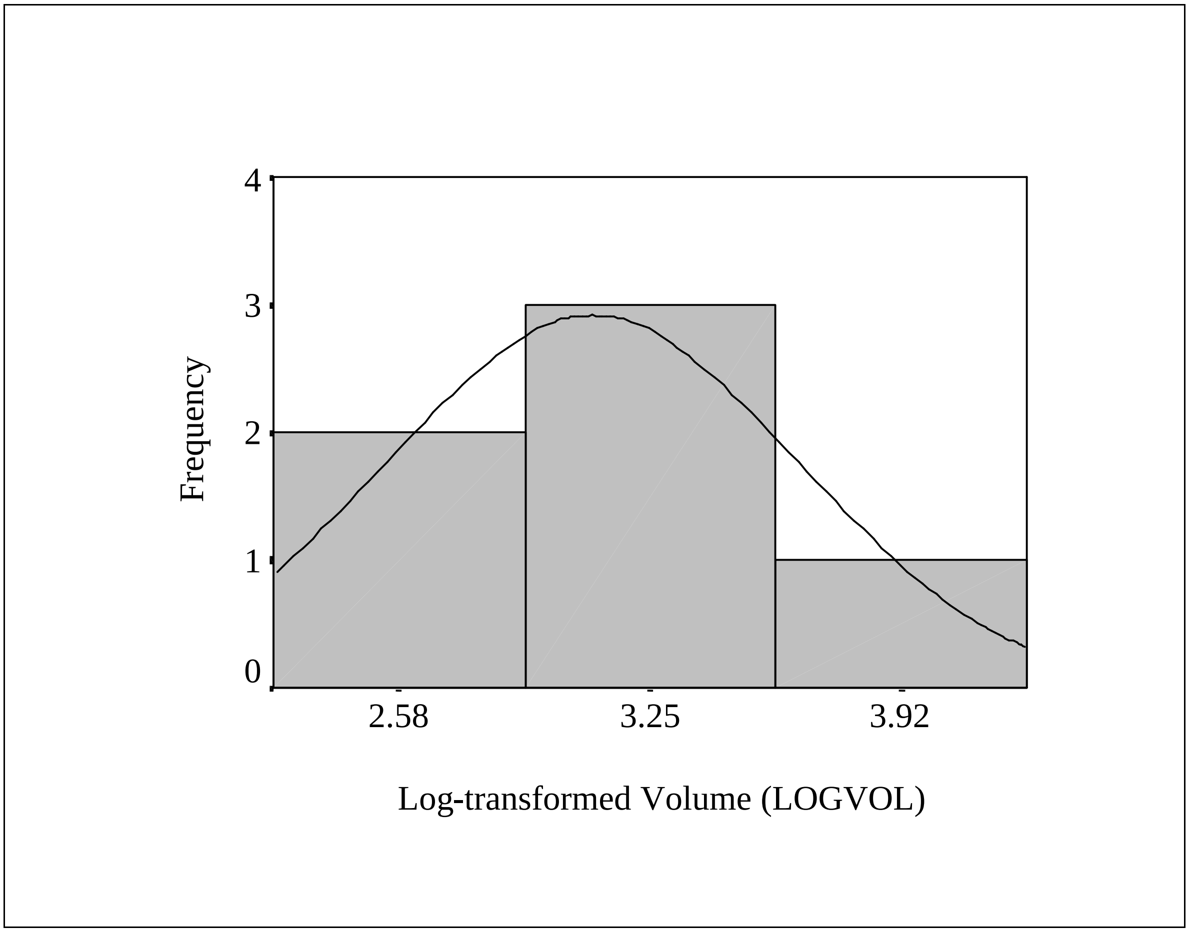

Figure 7.9 Histogram of the Log-transformed Volume of Deteriorated Concrete on Spalls below MLW (Variable “LOGVOL”) for Pontis™ Condition State 3

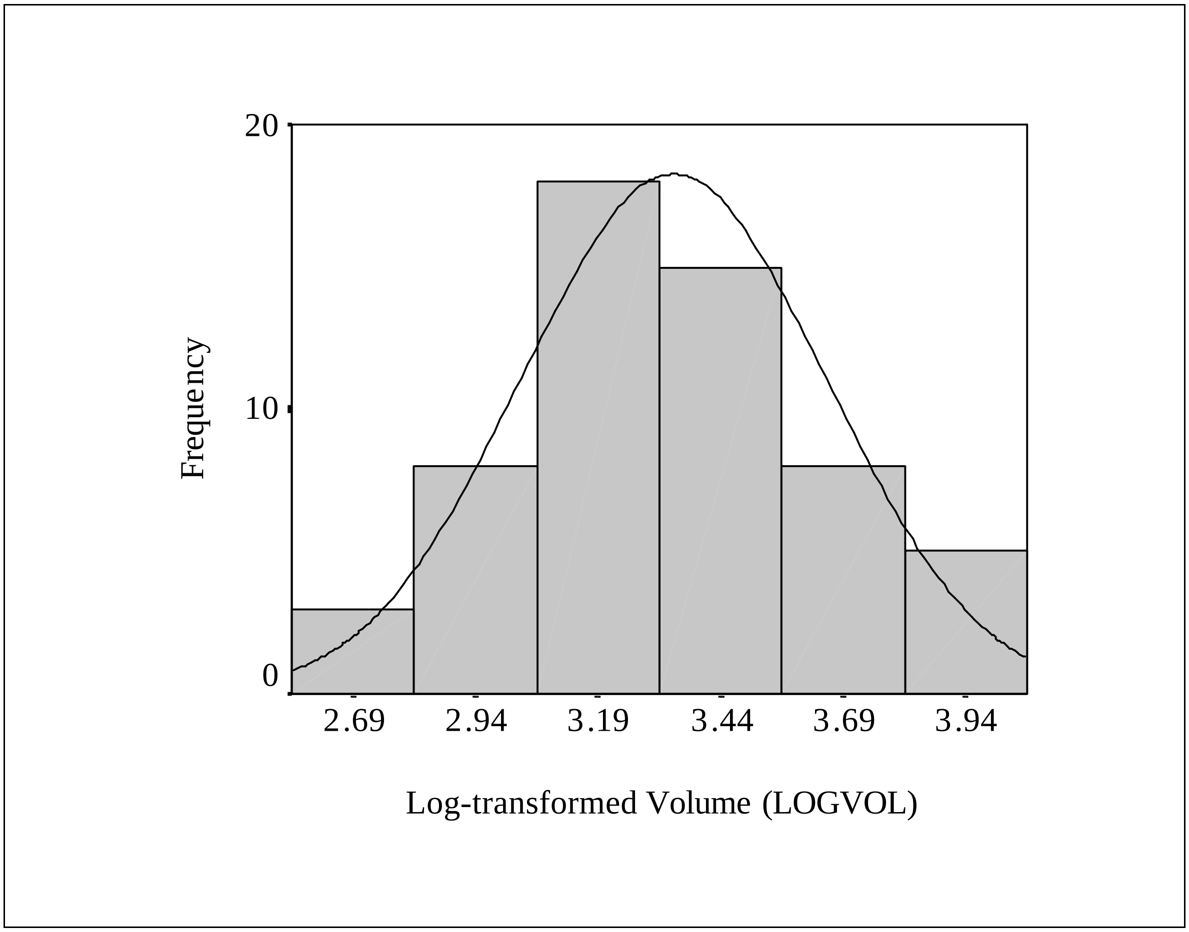

Figure 7.10 Histogram of the Log-transformed Volume of Deteriorated Concrete on Spalls above MLW (Variable “LOGVOL”) for Pontis™ Condition State 4

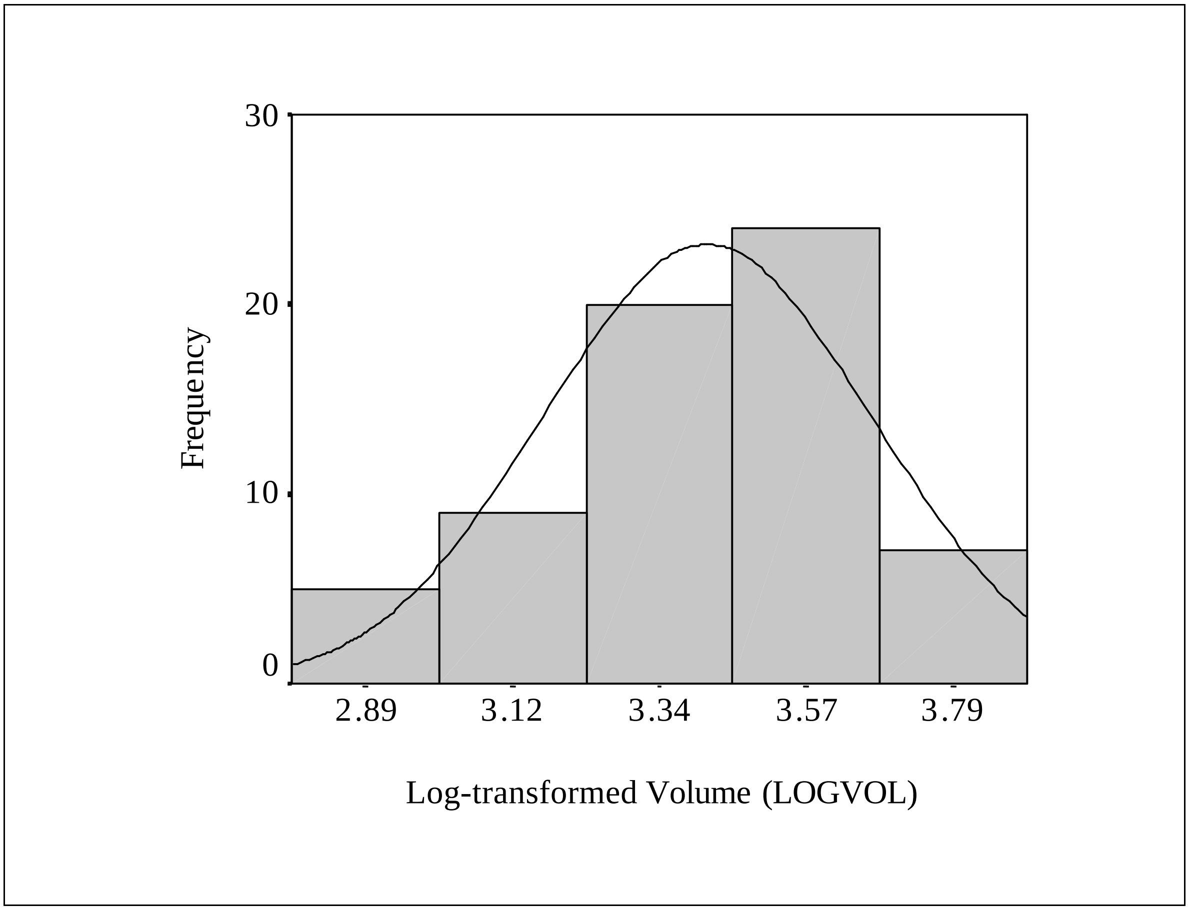

Figure 7.11 Histogram of the Log-transformed Volume of Deteriorated Concrete on Spalls below MLW (Variable "LOGVOL") for Pontis™ Condition State 4

A summary of the statistical parameters of the log-transformed variable is shown in Table 7.3 for spalls above MLW and in Table 7.4 for spalls below MLW. Outliers shown in Figure 7.4 were removed from the sample. Outliers were identified based on the criteria discussed in Section 2.12.1. For each Pontis™ Condition State, the ratio of the kurtosis and skewness to its respective standard error was greater than –2 and less than 2. The sample median and mean for the log-transformed data were close in value, as would be expected in a normal distribution. The expected range for at least 95 percent of the values were also very close to the observed values. Therefore, the author concluded that the data exhibited a normal distribution. The range of values and means of the deteriorated concrete volume in cubic feet (cu.ft.) calculated from the variable LOGVOL, for spalls above MLW are shown in Table 7.5. For Pontis™ Condition State 2, the average volume of deteriorated concrete in a spall was 0.1 cu.ft.; for Condition State 3, 0.9 cu.ft.; and for Condition State 4, 1.3 cu.ft. Similarly, the range of values and means of the deteriorated concrete volume in cubic feet (cu.ft.) calculated from the variable LOGVOL, for spalls below MLW are shown in Table 7.6. For Condition State 2 the average volume of deteriorated concrete in a spall was 0.1 cu.ft.; for Condition State 3, 0.7 cu.ft.; and for Condition State 4, 1.5 cu.ft.

Table 7.3 Summary of the Statistical Parameters of the Log-transformed Volume Variable "LOGVOL" for Spalls above MLW

Parameter	Pontis™ Condition State 2	Pontis™ Condition State 3	Pontis™ Condition State 4
Range of Values (LOGVOL)	0.6 - 3.4	2.4 - 3.8	2.6 - 4.0
Expected 95% Range of Values	1.1 - 3.6	2.6 - 3.8	2.7 - 4.0
Mean	2.38	3.17	3.34
Median	2.45	3.22	3.30
Standard Deviation	0.63	0.31	0.31
Skewness	-0.43	-0.40	0.06
Standard Error of Skewness	0.26	0.28	0.32
Skewness to Standard Error Ratio	-1.64	-1.44	0.20
Kurtosis	-0.20	-0.18	-0.37
Standard Error of Kurtosis	0.52	0.55	0.62
Kurtosis to Standard Error Ratio	-0.39	-0.33	-0.60

Table 7.4 Summary of the Statistical Parameters of the Log-transformed Volume Variable "LOGVOL" for Spalls below MLW

Parameter	Pontis™ Condition State 2	Pontis™ Condition State 3	Pontis™ Condition State 4
Range of Values (LOGVOL)	1.76 - 2.89	2.3 - 3.8	2.8 - 3.9
Expected 95% Range of Values	1.53 - 3.18	2.0 - 4.2	2.9 - 3.9
Mean	2.37	3.10	3.42
Median	2.44	3.14	3.44
Standard Deviation	0.42	0.55	0.25
Skewness	-0.261	-0.35	-0.50
Standard Error of Skewness	0.717	0.85	0.30
Skewness to Standard Error Ratio	-0.36	-0.41	-1.69
Kurtosis	-1.382	-0.88	-0.40
Standard Error of Kurtosis	1.4	1.74	-0.59
Kurtosis to Standard Error Ratio	-0.99	-0.50	0.68

Table 7.5 Volume Range and Average Volume of Deteriorated Concrete in a Spall above MLW for each Pontis™ Condition State Calculated from the Log-transformed Volume Variable "LOGVOL"

Parameter	Pontis™ Condition State 2	Pontis™ Condition State 3	Pontis™ Condition State 4
Volume Range of Deteriorated Concrete (cu.ft.)	0.0 - 1.4	0.1 - 3.3	0.2 - 5.8
Expected 95% Range of Values (cu.ft.)	0.0 - 1.4	0.2 - 3.3	0.2 - 5.8
Mean	0.1	0.9	1.3

Table 7.6 Volume Range and Average Volume of Deteriorated Concrete in a Spall below MLW for each Pontis™ Condition State, Calculated from the Log-transformed Volume Variable "LOGVOL"

Parameter	Pontis™ Condition State 2	Pontis™ Condition State 3	Pontis™ Condition State 4
Volume Range of Deteriorated Concrete (cu.ft.)	0.0 - 0.5	0.1 - 3.7	0.4 - 4.6
Expected 95% Range of Values (cu.ft.)	0.0 - 0.9	0.1 - 9.17	0.5 - 4.6
Mean	0.1	0.7	1.5

7.2.3 Crack Data

Crack data included data from six bridges located throughout Florida. These bridges are listed in Table 7.7. The FDOT (1970) characterizes crack damage using two parameters: (1) crack length and (2) crack class. FDOT uses the following scale to classify cracks based on the crack's width (CW):

$$\text{CLASS} = 1 \text{ if } 0 < \text{CW} < 1/64 \text{ inch}$$

$$\text{CLASS} = 2 \text{ if } 1/64 \text{ inch} \geq \text{CW} < 1/32 \text{ inch}$$

$$\text{CLASS} = 3 \text{ if } 1/32 \text{ inch} \geq \text{CW} < 1/16 \text{ inch}$$

$$\text{CLASS} = 4 \text{ if } 1/16 \text{ inch} \geq \text{CW} < 1/8 \text{ inch}$$

$$\text{CLASS} = 5 \text{ if } \text{CW} \geq 1/8 \text{ inch}$$

Inspection reports contained CW data for 372 cracks and crack length data for 361 cracks. Concrete piles that showed crack damage were classified in four Pontis™ Condition States. The crack data used in this section referred to damage above water. There was not enough data available to characterize crack damage below water, but the analytical process would be the same.

7.2.4 Crack Data Analysis

The purpose of the crack data analysis was to determine the distribution of the crack length for each Pontis™ Condition State. The variable "CLENGTH" represented the crack length, and the variable "LOGCL" represented the log-transformation of the variable "CLENGTH".

Table 7.7 Summary of Bridges Used in the Analysis of Crack Damage

Bridge ID	Bridge Name	Facility Carried	Number of Crack Data Sets	
			Length	Class
150107	Howard Frankland	I-275	1	6
720076	Mathews	S.R. 10A	71	75
700076	(Over Indian River)	S.R. 404	3	3
700142	(Over Indian River)	S.R. 404	4	4
720056	(Over Broward River)	S.R. 105	59	60
780075	(Over San Sebastian River)	S.R. 5	223	224

The boxplots of the variable "CLENGTH" and "LOGCL" for Pontis™ Condition State 1, 2, 3 and 4 are shown in Figures 7.12 and 7.13 respectively. Based on the boxplot graphs, the log transformed variable "LOGCL" was used for the analysis since it showed a more symmetric distribution than that of the variable "CLENGTH". The histograms of the log-transformed variable "LOGCL" for each Pontis™ Condition State are shown in Figures 7.14 through 7.16.

The author concluded from the analysis of the statistical parameters of the log-transformed variable "LOGCL", shown in Table 7.8, that the variable exhibited a normal distribution. Normality was accepted because the ratios of the skewness and kurtosis to its standard error were less than –2 or greater than +2. In addition, the values of the mean and median were a close value as expected in a normal distribution. Finally, at least 95 percent of the values in the sample were greater than the mean minus two times the standard deviation, and less than the mean plus two times the standard deviation. The range of values and the mean values for the crack length variable were calculated from the log-transformed variable “LOGCL” and are shown in Table 7.8.

The variable “CCLASS” was used to represent the crack class (width). The inspection report specified the crack class but not the actual width dimension. Therefore, it was not possible to find an average value for the CW. The crack class was used to relate crack data with corrosion data using neural networks. Neural networks were discussed in Section 2.12.4.

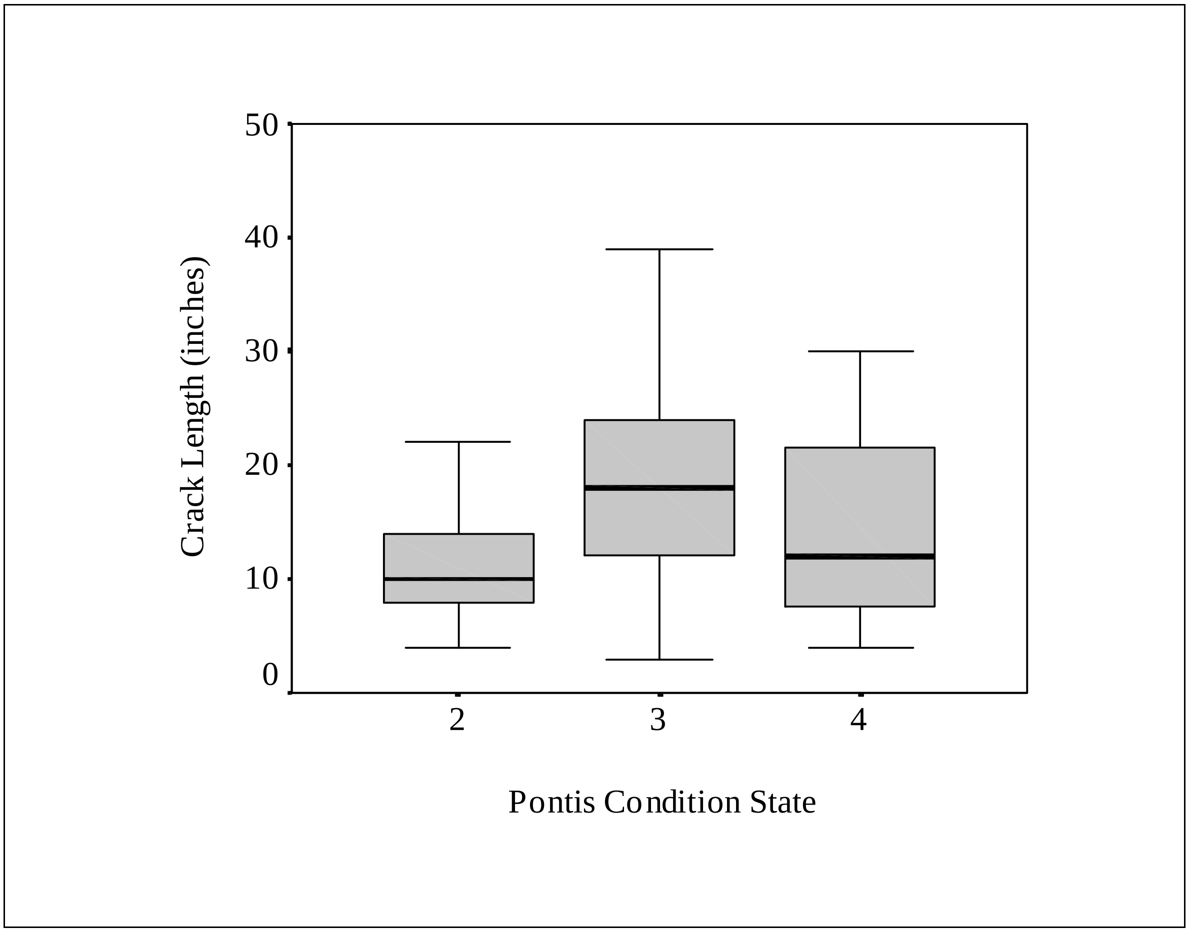

Figure 7.12 Boxplot Graph of the Crack Length (Variable "CLENGTH") for each Pontis™ Condition State

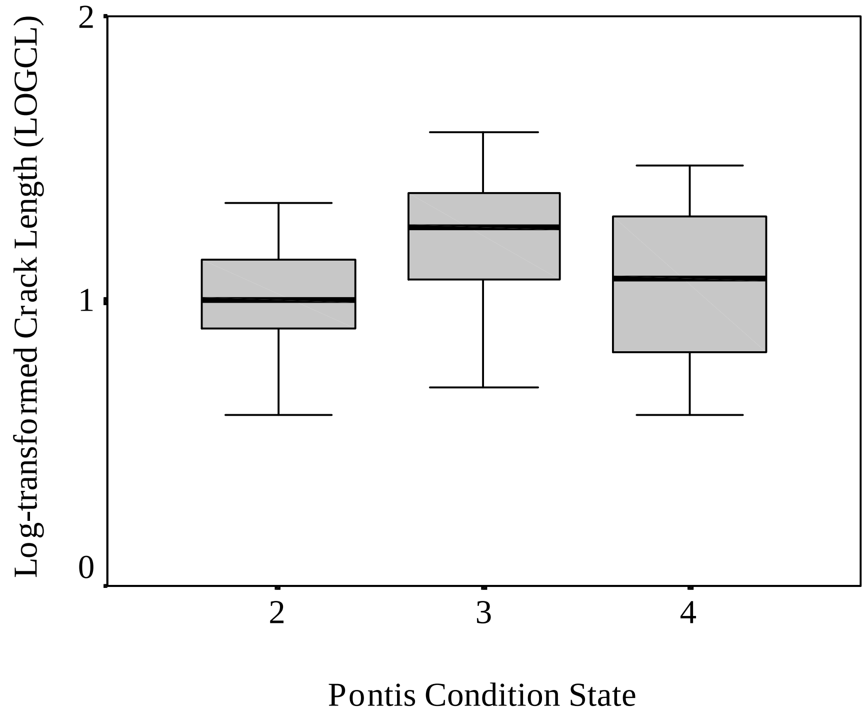

Figure 7.13 Boxplot Graph of the Log-transformed Crack Length (Variable "LOGCL") for each Pontis™ Condition State

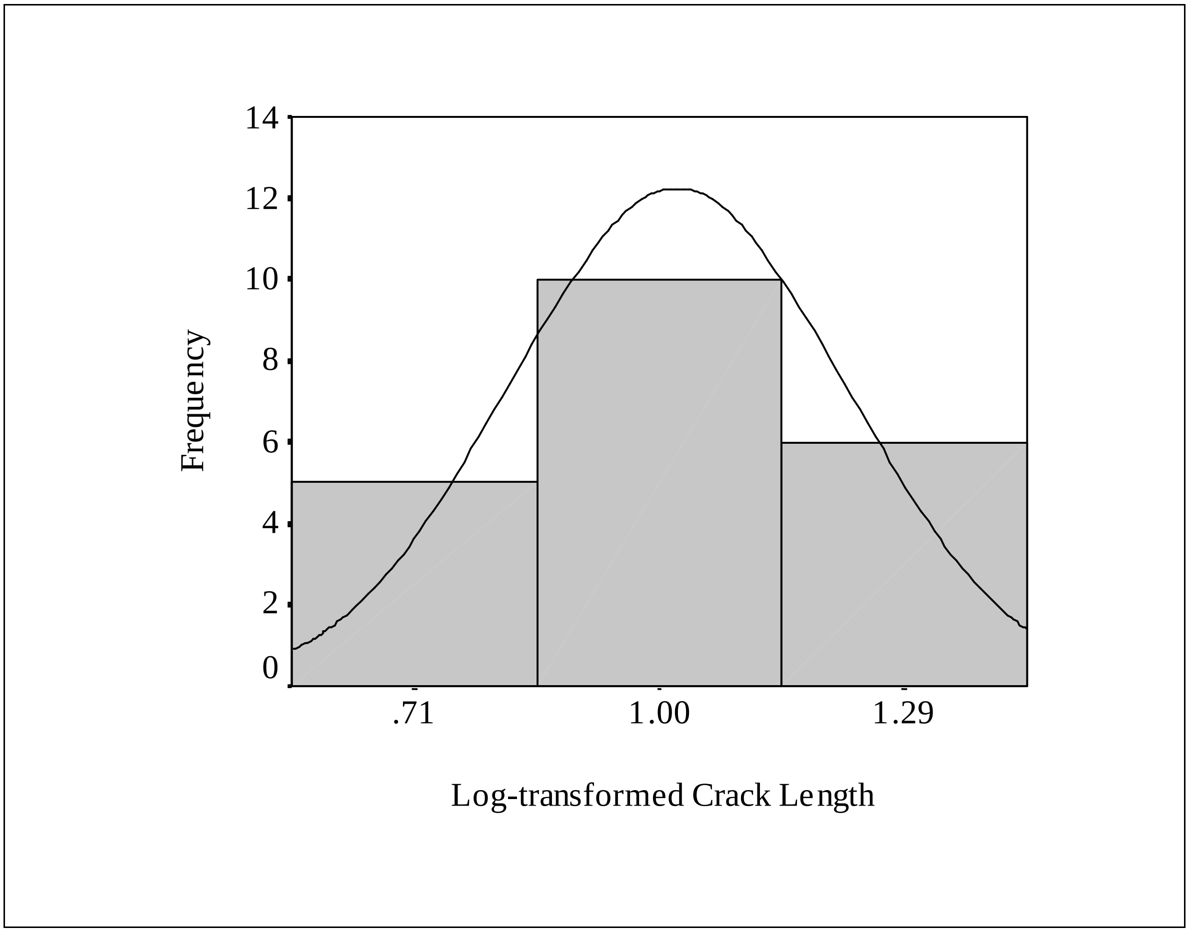

Figure 7.14 Histogram of the Log-transformed Crack Length Variable for Pontis™ Condition State 2

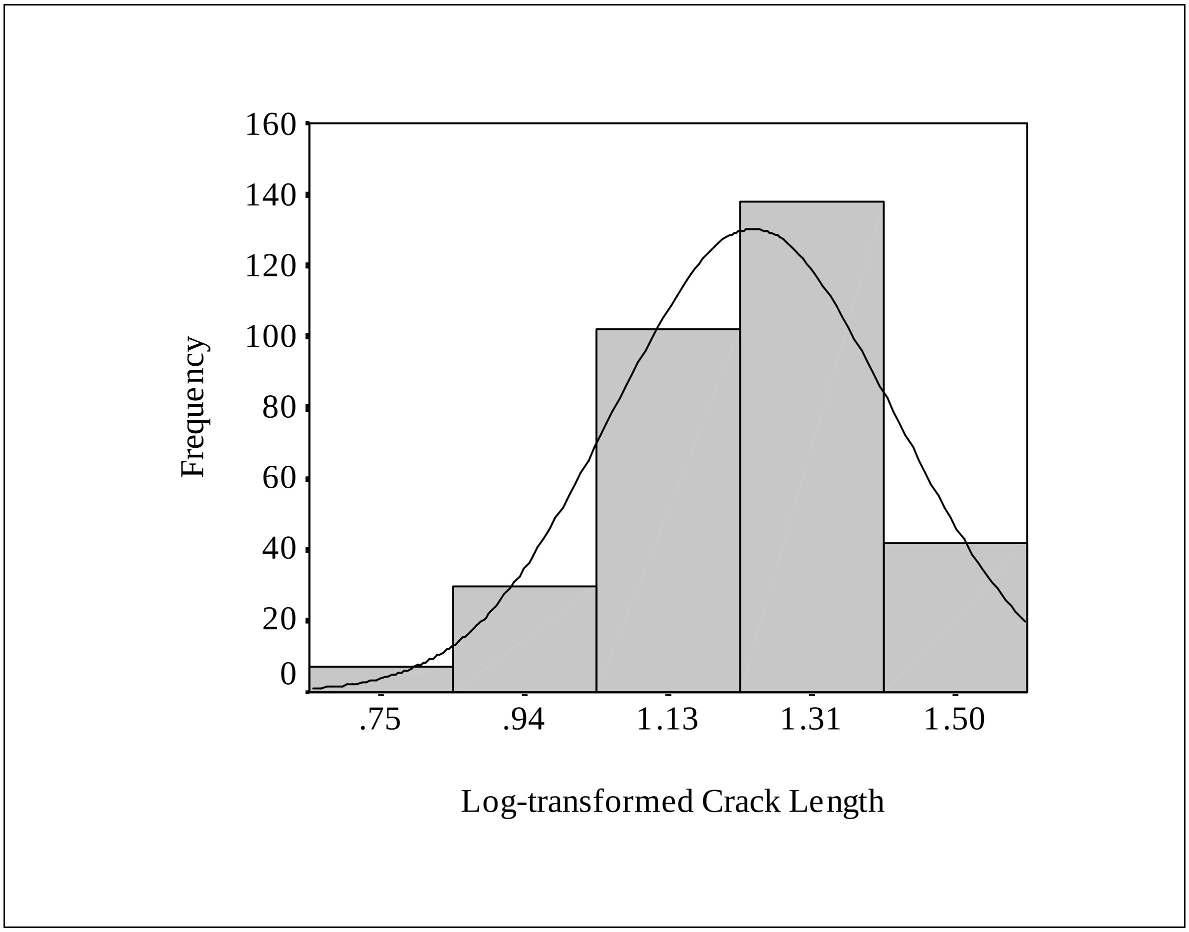

Figure 7.15 Histogram of the Log-transformed Crack Length Variable for Pontis™ Condition State 3

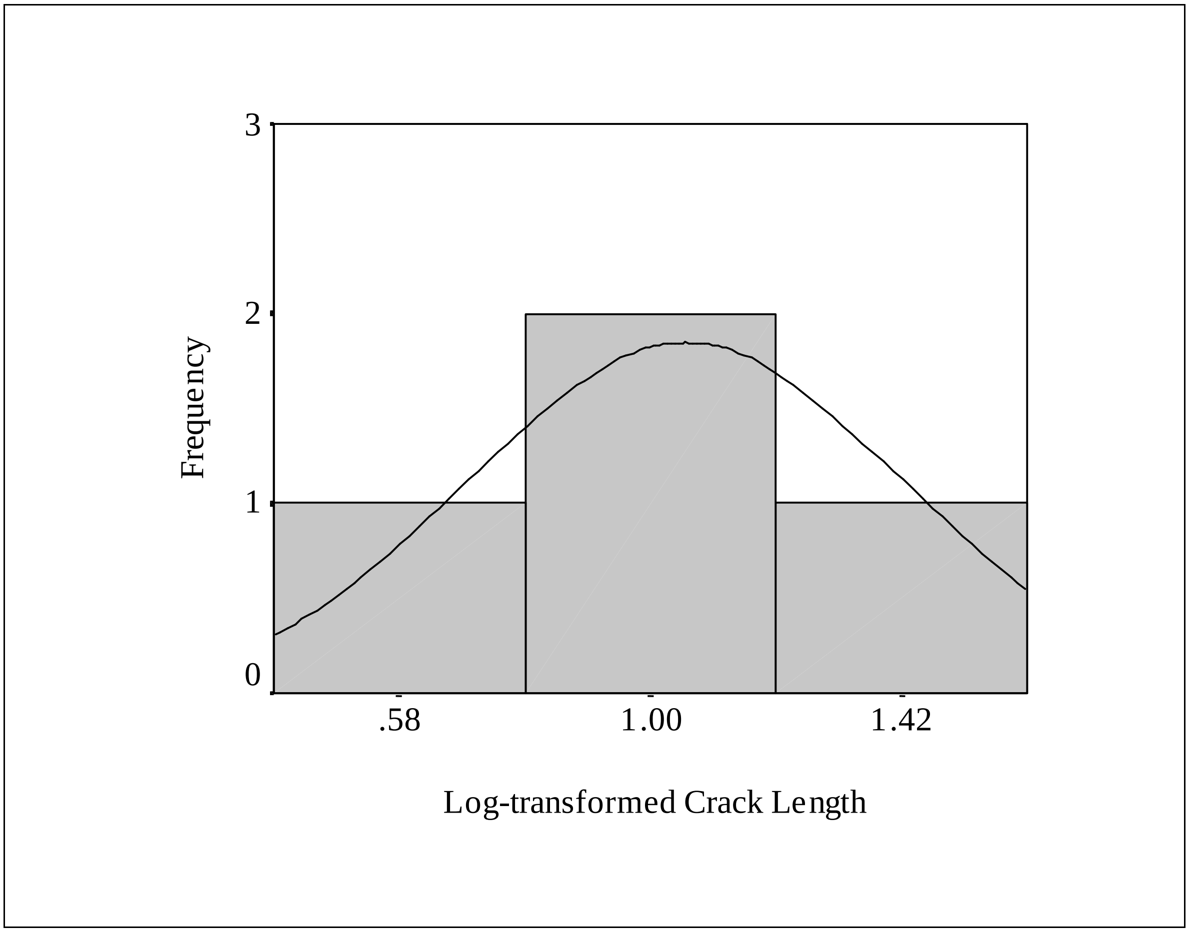

Figure 7.16 Histogram of the Log-transformed Crack Length Variable for Pontis™ Condition State 4

Table 7.8 Statistical Parameters of the Log-transformed Crack Length Variable

Parameter	Pontis™ Condition State 2	Pontis™ Condition State 3	Pontis™™ Condition State 4
Range of Values (LOGCL)	0.60 - 1.34	0.70 - 1.59	0.60 - 1.48
Expected 95% Range of Values	0.62 - 1.42	0.88 - 1.6	0.34 - 1.78
Mean	1.02	1.24	1.06
Median	1.0	1.26	1.08
Standard Deviation	0.20	0.18	0.36
Skewness	-0.141	-0.19	-0.31
Std. Error of Skewness	0.501	0.14	1.01
Skewness to Std. Error Ratio	-0.28	-1.39	-0.31
Kurtosis	-0.342	0.06	1.35
Std. Error of Kurtosis	0.972	.27	2.62
Kurtosis to Std. Error Ratio	-0.352	.24	0.52

Table 7.9 Crack Length Range and Average Crack Length for each Pontis™ Condition State Calculated from the Log-transformed Crack Length Variable “LOGCL"

Parameter	Pontis™ Condition State 2	Pontis™ Condition State 3	Pontis™ Condition State 4
Crack Length Range (in.)	4.0 - 22.0	5.0 - 39.0	4.0 - 3.0
Expected 95% Range of Values (in.)	4.2 - 26.3	7.6 - 39.8	2.2 - 60.3
Mean (in.)	10.5	17.5	11.5

7.3 Estimate Actual Damage Data from Inspection Data

The objective of this section was to demonstrate the use of neural networks to estimate actual damage quantities from detailed inspection data. Actual damage quantities were obtained from as-built reports prepared by the FDOT after a repair project was completed. Detailed inspection data were obtained from detailed inspection reports prepared by the FDOT before a repair was done. The author compared actual data to detailed inspection reports data and concluded that the actual damage was slightly larger than the damage predicted by detailed inspection data. However, the relation between the inspection data and actual damage data was not clear. Such relation was defined using neural networks.

7.3.1 Use of Neural Networks to Estimate Actual Spall Volume

The as-built data consisted of actual dimensions of deteriorated concrete volume removed from 35 spalls, located above MLW of the Seven-Mile Bridge (Bridge No. 900101). The bridge is located on the Florida Keys, in Monroe County, Florida. The FDOT under State Project No. 90000-3592 did the repairs and measured the dimensions of the spalls after all deteriorated concrete was removed from the damaged area. These as-built data were recorded on the as-built quantity report. The sizes of the spalls before the repairs were recorded in the corresponding inspection report also prepared by the FDOT.

Specifically, the relation between the size of the spall and the actual excavation volume were analyzed using neural networks. The author defined a variable “Factor” as the ratio between the actual spall excavation volume (defined in the as-built quantity report) and the estimated spall excavation volume (predicted by the dimensions of the spall in the inspection reports).

$$\text{Factor} = \frac{\text{Actual Spall Excavation Volume (As-built Quantities)}}{\text{Predicted Spall Excavation Volume (Inspection Report)}}$$

The variable "Factor" had values between 1 and 7. A second variable "FCATEGORY" was used to categorize the variable "Factor" into three groups A, B and C as follows:

$$\text{FCATEGORY} = \text{A if } 1 \geq \text{Factor} < 3$$

$$\text{FCATEGORY} = \text{B if } 3 \geq \text{Factor} < 5$$

$$\text{FCATEGORY} = \text{C if } 5 \geq \text{Factor} < 7$$

The input variables used to train the neural network were the spall length ("SPALL_L"), spall width ("SPALL_W") and the spall volume calculated from the spall dimensions given by the inspection report ("PLAN"). The output variable was "FCATEGORY". The inspection data assumed that the spall depth was 3 inches for all spalls because that was the design depth to the interior face of the reinforcement. The latter value (3 inches) compared well with the spall depth data described in Section 7.2.1. In the spall data sample from inspection reports discussed in Section 7.2.1, the spall depth distribution shows a normal distribution with both the mean and median spall depth of the sample equal to 2.4 inches.

Twenty-six data rows were used to train the network (roughly 75 percent of the available data), and eight data rows were used to test the accuracy of the neural network model. The data used to test the neural network were not included in the data used to train it. The 26 data rows, used to train the neural network, contained both the input variables as well as the output variables. From the input data, the network learned that a given spall width, spall length and estimated excavation volume belonged to one of the three categories defined by the variable “FCATEGORY”.

The eight data rows used to test the model had the input data only. The model classified correctly all eight rows of data used to test the model. Results provided by the model are shown in Table 7.10. The results included the category in which the model classified the data and the probability of each row of data belonging to each of the several categories. The results of the neural network were applied using a dynamic probability tree shown in Figure 7.17. This probability tree differed from others discussed in the literature (Diekman 1998) in that the probabilities were generated for each set of data by the neural network based on the unique dimensions of the spall. Therefore, probabilities were not fixed, but were changing constantly, thus the name “dynamic” probability tree. By predicting the probability that the data belonged to one of the three categories, the corresponding range of deterioration for each category could also be defined. The lower and upper limit of each range defined by the variable “FCATEGORY” was multiplied by both the respective probability and the excavation volume predicted by the inspection report for the given spall as shown in Figure 7.17 and 7.18. The new range, calculated as described previously, was the as-built excavation volume range estimated by the model. The total volume of concrete to be removed, as predicted by the model, was the sum of all the estimated excavation volume ranges and was between 35 cu.ft. to 74 cu.ft. The actual volume of concrete removed, as reported in the as-built quantities, was 43.0 cu.ft. This latter value (43.0 cu.ft.) was within the range predicted by the model.

Table 7.10 Comparison of Neural Network Model Results and Actual Values of the Variable "Factor"

Data ID	Spall Length inches	Spall Width inches	Estimated Excavation Volume inch^3	Neural Network Classification	Probability A	Probability B	Probability C	Factor
27	26	66	7.22	A	0.648	0	0.352	1.46
28	32	22	0.54	A	0.508	0.492	0	1.91
29	29	47	3.02	A	1	0		2.21
30	9	46	3.05	A	1	0	0	2.43
31	25	42	2.41	A	0.999	0.001	0	2.64
32	10	27	1.08	A	1	0	0	2.93
33	33	54	1.22	B	0	0.960	0.04	3.23
34	26	37	1.03	B	0	0.997	0.003	3.46

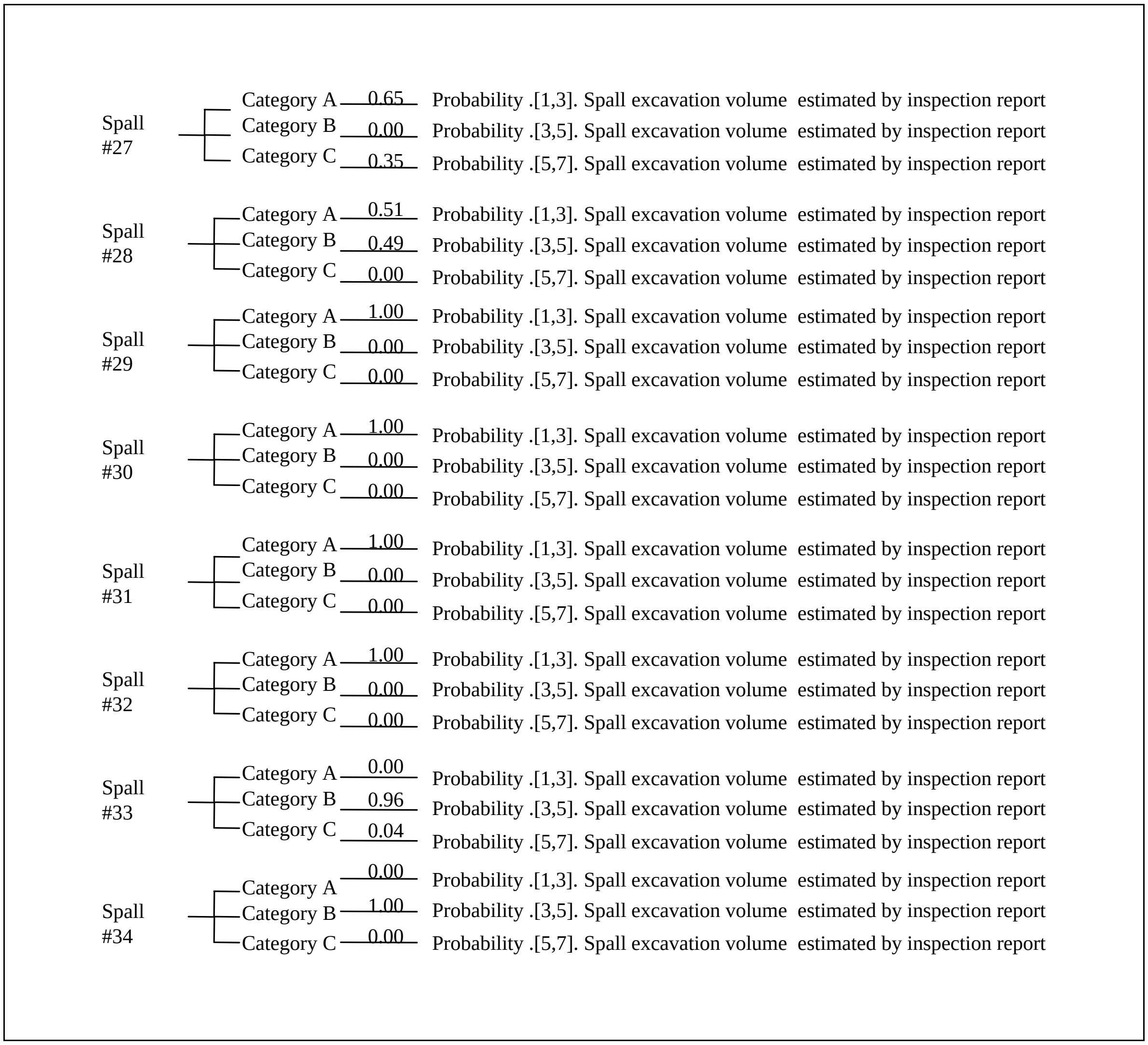

Figure 7.17 Dynamic Probability Tree Used to Estimate the Actual Excavation Volume

Spall #27
- Category A = (0.65) [1, 3] (7.22) = [4.69, 14.08]
- Category B = (0.0) [3 ,5] (7.22) = [0, 0]
- Category C = (0.35) [5, 7] (7.22) = [12.64, 17.69]

Spall #28
- Category A = (0.51) [1, 3] (0.54) = [0.28, 0.83]
- Category B = (0.49) [3, 5] (0.54) = [0.79, 1.32]
- Category C = (0.00) [5, 7] (0.54) = [0, 0]

Spall #29
- Category A = (1.0) [1, 3] (3.02) = [3.02, 9.06]
- Category B = (0.0) [3, 5] (3.02) = [0, 0]
- Category C = (0.0) [5, 7] (3.02) = [0, 0]

Spall #30
- Category A = (1.0) [1, 3] (3.05) = [3.05, 9.15]
- Category B = (0.0) [3, 5] (3.05) = [0, 0]
- Category C = (0.0) [5, 7] (3.05) = [0, 0]

Spall #31
- Category A = (1.0) [1, 3] (2.41) = [2.41, 7.23]
- Category B = (0.0) [3, 5] (2.41) = [0, 0]
- Category C = (0.0) [5, 7] (2.41) = [0, 0]

Spall #32
- Category A = (1.0) [1, 3] (1.08) = [1.08, 3.24]
- Category B = (0.0) [3, 5] (1.08) = [0, 0]
- Category C = (0.0) [5, 7] (1.08) = [0, 0]

Spall #33
- Category A =(0.0) [1, 3] (1.22) = [0, 0]
- Category B =(0.96) [3, 5] (1.22) = [3.51, 5.86]
- Category C = (0.04) [5, 7] (1.22) = [0.24, 0.34]

Spall #34
- Category A =(0.0) [1, 3] (1.03) = [0, 0]
- Category B =(1.0) [3, 5] (1.03) = [3.09, 5.15]
- Category C = (0.0) [5, 7] (1.03) = [0, 0]

Total Volume Range of Concrete to be Removed = [35, 74]

Actual Volume of Concrete Removed = 43

Figure 7.18 Volume Range Calculated Using the Dynamic Probability Tree

7.3.2 Reinforcement Corrosion Data

The reinforcement corrosion data used in the damage assessment model were part of the as-built quantities reports created by the FDOT after completion of four repair projects in bridges listed in Table 7.11. As-built quantities were used because it was difficult to evaluate corrosion damage, unless unsound concrete was removed. The as-built quantities reports, or "chipping logs", as they were called by the FDOT, described the number of corners and faces removed. In addition, the chipping log of bridge 720076 included transverse reinforcement corrosion data and that of bridge 720063 included longitudinal reinforcement data.

Table 7.11 Summary of Bridges Used in the Analysis of Reinforcement Corrosion Data

Bridge ID	Bridge Name	Facility Carried	Number of Data Sets		
			Con-crete Damage	Transverse Reinforce-ment	Longitudinal Reinforce-ment
720076	Mathews	S.R. 10A	195	183	0
720063	(Over Haulover Creek)	S.R. 105	41	0	41
720044	(Over San Pablo River)	S.R. 10A	60	0	0
720056	(Over Broward River)	S.R. 105	11	0	0

7.3.3 Neural Network Analysis of the Transverse Reinforcement Corrosion Data

The chipping log for Bridge 720076 included 183 repair data sets for transverse reinforcement, as well as the numbers of corners and faces removed for each pile. In addition, an inspection report by the FDOT provided concrete deterioration data for the same piles before repair. Specifically, concrete deterioration data included crack length, crack class and spall class. The purpose of the neural network analysis was to determine the relation between concrete deterioration (cracks and spalls) and transverse reinforcement corrosion data. Several models were studied to define the combination of input and output data that gave the best results. Two arrangements of input data were used. The first one contained the crack length, crack class and spall class only. The second one contained the same input variables as the first one, but it also included the number of corners and faces removed from the pile.

Three arrangements of output data were analyzed using neural networks. The first output data arrangement defined whether or not transverse reinforcement needed to be replaced. The second one defined the number of transverse reinforcements that needed to be replaced. Specifically, the type of transverse reinforcement considered was stirrup since that data were available. The third one classified the number of stirrups to be replaced into three categories: (A) replace 0 stirrups, (B) replace 1,2 or 3 stirrups and (C) replace 4 or 5 stirrups. In addition, to define the impact that the number of data sets used to train the network had on the accuracy of the models, the number of data sets were varied for each model. Each one of the models were trained using either 10 times the number of input variables (50 sets), one half the total number of data sets (91 sets), or 2/3 the total number of data sets (122). The neural network accuracy was determined based on the percentage of data sets that were classified correctly. A summary of the results for each one of the models described previously is shown in Table 7.12.

For the neural network with the higher accuracy (96 percent), the number of data sets used to train the model was 50 sets, and the input variables were crack length, crack class and spall class. The output variable was whether or not to replace the stirrups. The author could not define which input variable combination was most informative since the accuracy was almost the same (94 percent) for neural networks with different input combinations in which the output was whether or not to replace the stirrups and which were trained using 91 sets of data. For these latter neural networks, there was a variation in accuracy depending on the number of data sets used to train the data. Therefore, the author concluded that the number of data sets used to train the neural network rather than the number of input variables might affect the accuracy of the neural network. The neural network poorly predicted the number of stirrups to be replaced. In such a case, the accuracy of the neural network was very low (20 percent to 50 percent). The accuracy of the neural network was also low when the output variable was the number of stirrups to be replaced grouped in three categories (61 percent to 62 percent). Based on the results the author selected the neural network that used as input variables the crack length, the crack class and the spall class. The output variable selected was whether or not to replace the stirrups. The number of data sets selected to train the network was 91.

Table 7.12 Comparison of the Neural Network Parameters Used to Analyze the Relation between Concrete Deterioration and Transverse Steel Reinforcement

<table>
<tr><th>Input Variable</th><th>Output Variable</th><th>Number of Data Sets (Training)</th><th>Number of Data Sets (Testing)</th><th>Accuracy</th></tr>
<tr><td rowspan="9">Crack Length
Crack Class
Spall Class</td><td rowspan="3">Replace stirrups (Yes/No)</td><td>50</td><td>133</td><td>96%</td></tr>
<tr><td>91</td><td>92</td><td>94%</td></tr>
<tr><td>122</td><td>61</td><td>92%</td></tr>
<tr><td rowspan="3">Number of stirrups to be replaced</td><td>50</td><td>133</td><td>20%</td></tr>
<tr><td>91</td><td>92</td><td>50%</td></tr>
<tr><td>122</td><td>61</td><td>43%</td></tr>
<tr><td rowspan="3">Replace: (A) 0 stirrups, (B) 1, 2 or 3 stirrups, (C) 4 or 5 stirrups</td><td>50</td><td>133</td><td>70%</td></tr>
<tr><td>91</td><td>92</td><td>72%</td></tr>
<tr><td>122</td><td>61</td><td>61%</td></tr>
<tr><td rowspan="9">Crack Length
Crack Class
Spall Class
Removed Corners
Removed Faces</td><td rowspan="3">Replace stirrups (Yes/No)</td><td>50</td><td>133</td><td>89%</td></tr>
<tr><td>91</td><td>92</td><td>94%</td></tr>
<tr><td>122</td><td>61</td><td>93%</td></tr>
<tr><td rowspan="3">Number of stirrups to be replaced</td><td>50</td><td>133</td><td>44%</td></tr>
<tr><td>91</td><td>92</td><td>39%</td></tr>
<tr><td>122</td><td>61</td><td>39%</td></tr>
<tr><td rowspan="3">Replace: (A) 0 stirrups, (B) 1, 2 or 3 stirrups, (C) 4 or 5 stirrups</td><td>50</td><td>133</td><td>66%</td></tr>
<tr><td>91</td><td>92</td><td>72%</td></tr>
<tr><td>122</td><td>61</td><td>61%</td></tr>
</table>

To estimate quantities, it was not only necessary to define whether or not stirrups need to be replaced, but it was also necessary to know the number of stirrups to be replaced. Since the number of stirrups to be replaced could not be predicted by the neural networks accurately, the author calculated the discrete probabilities of replacing 1, 2, 3, 4 or 5. These latter probabilities were calculated based on the relative frequency of the number of stirrups replaced as observed in the as-built data, and they are shown in Table 7.13. Using these probabilities, a dynamic probability tree, shown in Figure 7.19 determined the number of stirrups that needed to be replaced. The neural network calculated the probability that stirrups needed to be replaced on a given pile. This probability was multiplied by both the probability of replacing a given number of stirrups, times the number of stirrups to be replaced. Only a section of the dynamic probability tree, which corresponded to a single pile, is shown in Figure 7.19 (a) and (b).

Table 7.13 Probability of Replacing a Given Number of Stirrups

Description	Probability
Probability of replacing 1 stirrup	0.073
Probability of replacing 2 stirrups	0.293
Probability of replacing 3 stirrups	0.402
Probability of replacing 4 stirrups	0.207
Probability of replacing 5 stirrups	0.024

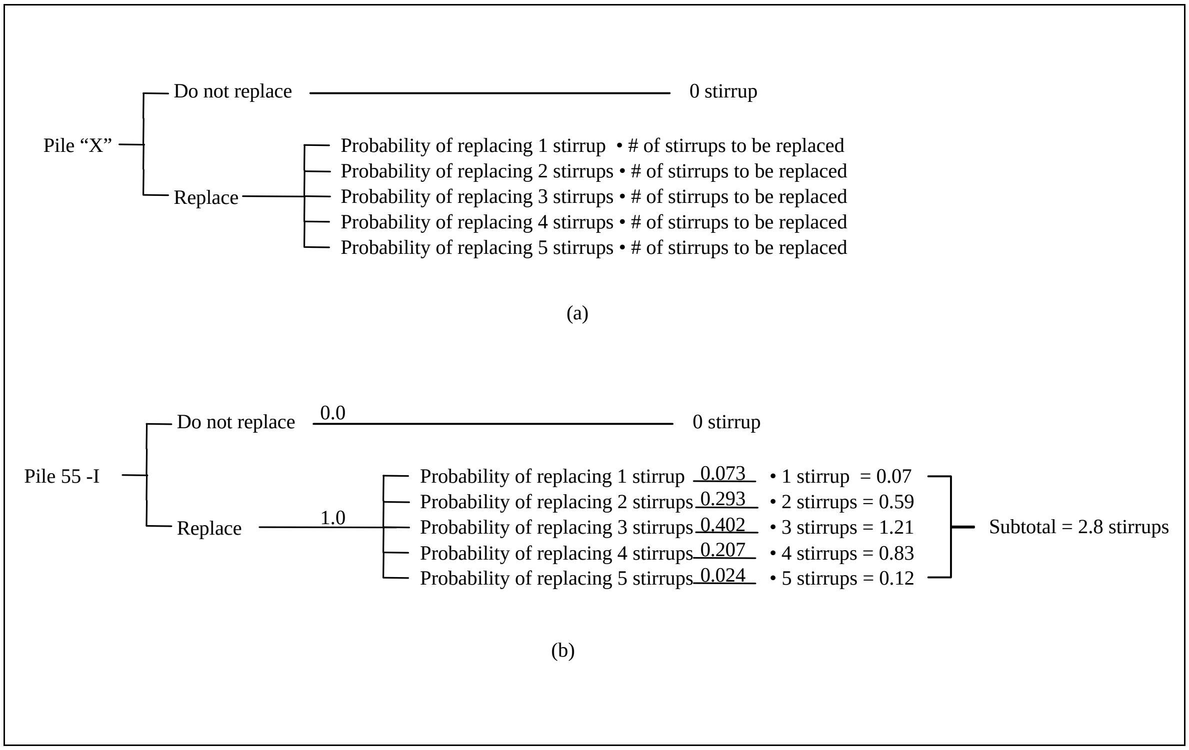

Figure 7.19 (a) Dynamic Probability Tree (b) Sample Values used in the Dynamic Probability Tree that Calculated the Number of Stirrups to be Replaced

As an example, values corresponding to pile "I", span 55, of the Mathews Bridge are shown in Figure 7.19 (b). The probability of replacing 1, 2, 3, 4 or 5 stirrups were calculated using the same data sets used to train the network, so that the remaining data sets could be used to test both the neural network and the dynamic probability tree. Applying the dynamic probability tree to the 92 data sets remaining, the total number of stirrups that need to be replaced on the bridge was calculated as 259. The actual number of stirrups replaced on the 92 piles considered was 266, which is 2.67 percent higher than the number of stirrups calculated by the dynamic probability tree.

7.3.4 Neural Network Analysis of the Longitudinal Reinforcement Corrosion Data

The longitudinal reinforcement corrosion data were composed of 41 data sets recorded in the as-built report or chipping log prepared by the FDOT for Bridge 720063, over Haulover Creek. The input variables were the number of corners removed, the number of faces removed and the Pontis™ Condition State. The output variable was the number of reinforcing bars with more than 25 percent cross section loss. FDOT requires using structural jackets when two or more longitudinal reinforcements exhibit 25 percent or more cross section loss. The neural network was trained with 30 data sets and tested with the remaining 11 data sets. The accuracy of the network, with the parameters described was 91 percent. The neural network generated the probability of a pile having 0, 1, 2, 3 or 4 bars, which have more than 25 percent cross section loss. In a pile, the number of reinforcing bars is equal to or larger than 4. However, the probability of having more than 4 bars with 25 percent cross section loss could not be defined because there were not data available. Since the results were based on limited data, the author recommended using the results of the neural networks described in this section as a preliminary study. Collection of more data is required to determine the actual corrosion behavior of the pile, and it is recommended for future research.

Nevertheless, based on the encouraging results obtained from such a limited sample and to illustrate the methodology, the author developed a dynamic probability tree using the probabilities generated by the neural network. Only a section of the dynamic probability tree, which corresponds to a single pile, is shown in Figures 7.20 (a) and (b).

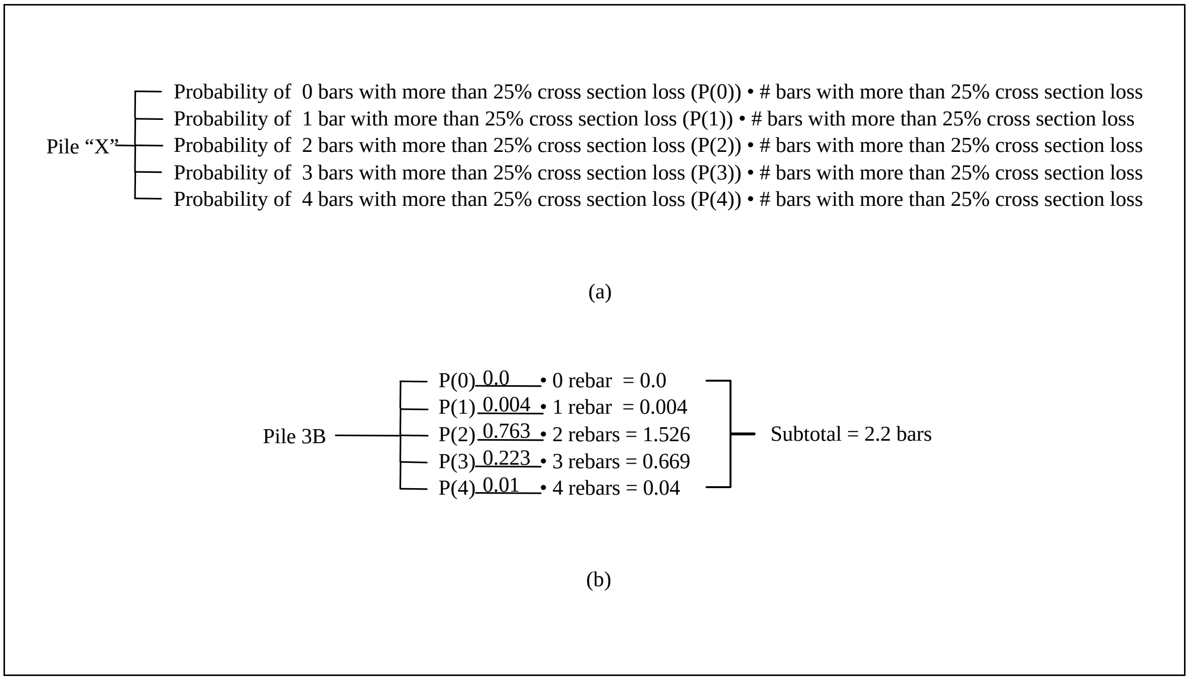

Figure 7.20 (a) Dynamic Probability Tree (b) Sample Values Used in the Dynamic Probability Tree that Calculated the Number of Bars Having more than 25 Percent Cross Section Loss

Values corresponding to the 11 piles used to test the model are shown in Table 7.15. For such piles, as reported in the chipping log, there were a total of 12 bars that had more than 25 percent cross section loss. According to the results given by the dynamic probability tree, 12.55 bars (or 13 bars) had 25 percent or more cross section loss; that is 4.58 percent more than the actual quantities.

Table 7.14 Probabilities Values Used in the Dynamic Probability Tree for Piles Used to Test the Neural Network

Pile	Probability of having 0, 1, 2, 3 or 4 bars with more than 25% section loss					Number of bars having more than 25% section loss	
	P(0)	P(1)	P(2)	P(3)	P(4)	Estimated	Actual
3A	0.992	0.008	0.0	0.0	0.0	0.0	0
3B	0.0	0.004	0.763	0.223	0.01	2.2	2
3C	0.0	0.004	0.763	0.223	0.01	2.2	2
3D	0.995	0.005	0.0	0.0	0.0	0.0	0
4A	0.791	0.197	0.001	0.006	0.005	0.2	0
4B	0.974	0.021	0.0	0.005	0.0	0.0	0
4C	0.974	0.021	0.0	0.005	0.0	0.0	0
4D	0.992	0.008	0.0	0.0	0.0	0.0	0
5A	0.0	0.003	0.747	0.239	0.01	2.3	2
5B	0.0	0	0.001	0.911	0.088	3.1	3
5C	0.0	0	0.618	0.363	0.019	2.4	3

7.4 Conclusions

The analysis in this chapter demonstrated that the data which described concrete deterioration, that is spall width, length and depth as well as crack length, showed defined normal distribution for each Pontis™ Condition State. Therefore, it could be possible to define damage default values for each Pontis™ Condition State using quantitative terms, based on the mean values and ranges observed for each damage parameter. Results presented in this chapter allowed the characterization of concrete spall parameters for each Pontis™ Condition State above and below water (MLW). However, the crack damage data referred only to damage located above water. Future research is recommended to collect and analyze data for damage below water.

The analysis in this chapter also demonstrated that actual damage quantities were larger than those predicted by detailed inspection data. Neural networks and probability trees could be combined into dynamic probability trees to estimate actual damage quantities from detailed inspection reports. Such dynamic probability trees were a tool to estimate actual damage quantities based on inspection data, specifically volume of concrete to be removed, and both transverse and longitudinal reinforcement replacement due to corrosion damage. The available data used by the neural network were limited and referred to individual bridges. Also, the data referred only to damage above the water. Nevertheless, the results obtained when testing the neural network on each individual bridge were acceptable. Testing the neural network with a data set different from the data sets used to train the network validated the neural networks. Based on these encouraging results, future research is recommended to collect more as-built data, so that the same methodology can be tested and applied to a greater sample

CHAPTER VIII

VALIDATION

8.1 Introduction

The Damage Assessment Model, Construction Process Model and Parametric Quantity Model were applied to FDOT Contract No. 404106-1-52-01 (Gandy Bridge Repair). The main objective was to validate the models by comparing the repair quantities estimated by the models at the pre-design stage to those defined in the design plans after all construction documents were completed. A secondary objective was to validate the Damage Assessment Model, Construction Process Model and Parametric Quantity Model by proving that the models were able to mimic the engineering process involved in the repair of the piles of the Gandy Bridge, which consisted of defining the damage on the bridge piles, defining the construction tasks and estimating quantities.

Construction tasks and quantities were calculated using inspection data available before the repair project was constructed and design default values proposed in the models, since that would have been the data available at the pre-design stage. Results generated by the models were compared to the quantities estimated for the project as shown in the project design plans.

8.2 Project Description

FDOT Contract No. 404106-1-52-01 involved the repair of four concrete piles on the Gandy Bridge (Bridge No. 100300) using integral CP jackets with sacrificial anodes. The contract included a repair project of the Howard Frankland Bridge as well.

The Gandy Bridge carries the road US 92 and extends two miles over Old Tampa Bay joining Tampa and St. Petersburg, Florida. The Howard Frankland Bridge is approximately three miles East of the Gandy Bridge and carries the highway I-275 over Old Tampa Bay joining Tampa and St. Petersburg as well.

Parsons Brinckerhoff Quade & Douglas designed the repair project, prepared the plans and estimated quantities. Prior to design, Parsons Brickerhoff Quade & Douglas conducted a detailed inspection of the Gandy Bridge before the repair construction project started. The inspection report findings included damage existing on bridge piles, beams and footings (FDOT (j)).

8.3 Validation of the Damage Assessment Model

The validation of the Damage Assessment Model consisted of proving that the an electronic format compatible with the Pontis™ database could maintain data on damage existing on the concrete piles of the Gandy Bridge using quantitative values that referred to a specific type of damage. Figure 8.1 shows a report generated by the Damage Assessment Model using the same query and report wizard described in Example 4.1.

EXISTING DAMAGE ON A SPECIFIC BRIDGE

Bridge # 100300

Prestressed concrete pile # 2 SW on span 64 has the following damage(s):

- Delamination damage located above MLW
  - delamination width = 12 inch
  - delamination length = 79 inch

Prestressed concrete pile # 4 NE on span 116 has the following damage(s):

- Spall damage located above MLW
  - spall width = 12 inch
  - spall depth = 3 inch
  - spall length = 79 inch

Prestressed concrete pile # 6 SW on span 248 has the following damage(s):

- Spall damage located above MLW
  - spall width = 12 inch
  - spall depth = 6 inch
  - spall length = 24 inch

Prestressed concrete pile # 7 SW & NW on span 238 has the following damage(s):

- Spall with exposed steel damage located underwater
  - spall width = 20 inch
  - spall depth = 9 inch
  - spall length = 47 inch

Thursday, June 03, 2004

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Figure 8.1 Report Generated Using Damage Data Stored in the Damage Assessment Model for The Gandy Bridge

The inspection data corresponding to the piles of the Gandy Bridge were stored in the Damage Assessment Model using the “damage” Table. A portion of this table containing only the data related to the Gandy Bridge is shown in Table L.1. As discussed in previous chapters, each entity described in either the Damage Assessment Model, Construction Process Model or Parametric Quantity Model, was used to develop a table in the sample database which had the same name as the name used for the entity. It is important to note that in the sample database there was a single “damage” Table, which contained damage data corresponding to the Gandy, as well as other inspection data that referred to other elements and bridges. In this chapter, only portions of the data contained in the sample database tables are shown, with the understanding that such tables might contain other data described previously in other chapters or appendices.

The author encountered several problems associated with lack of detail on inspection data for pile number 7 on span 238. The data combined the spall dimensions of two spalls into a single spall length, width and depth but did not specify the dimensions corresponding to each spall. Another problem associated with the inspection data of this pile was that it stated that the damage was underwater but did not provide a dimension to locate the damage with respect to MLW. Misrepresentation of the data might result if one of the default pile sections was used because such sections had a specific damage location range associated with them. Thus if a default pile section was used for pile number 7 on span 238, it would add extraneous data that were not defined in the detailed inspection report. To avoid misrepresentation of the data, the author created a “user” defined section called “underwater” and added to the table defining the sections of the pile elements. Such a definition was only qualitative, and did not provide a specific value as shown in Table L.2.

The knowledge rules in the Construction Process Model were based on the default section definitions of the pile element. For user defined sections, the Construction Process Model asked the user to manually input the location of the damage in order to trigger the knowledge rule that defined the type of equipment required to access the pile. Thus, the author assumed a value and provided that value as a user input when requested by the Construction Process Model. This latter value was not stored in the damage assessment to prevent mixing assumed data with actual inspection data.

It is important to note that the knowledge rules in the Construction Process Model that were triggered by the location of the damage with respect to the water could be automatically implemented if the location of the damage was known, so that it could be characterized with one of the sections already defined in the model.

Another problem encountered on the existing inspection data was that for pile number 7 on span 238 the inspection data stated that there was reinforcement exposure but did not mention whether there was corrosion, cross section loss or an unsupported reinforcement length. To overcome this problem, a new type of damage called “spall with exposed steel” was defined which was characterized by the parameters “spall length”, “spall width” and “spall depth”. These data were stored in the database in the tables defining the damage and the damage parameter types (“damagedef” and “parameterdef” tables) and are shown in Table L.3 and L.4.

Problems related to lack of detail in the inspection data could have been avoided, if while inspecting a bridge, all parameters describing the existing damage were recorded.

8.4 Validation of the Construction Process Model

The validation of the Construction Process Model consisted of demonstrating that all construction tasks required in the design plan of the FDOT Project No. 404106-1-52-01 were considered by the Construction Process Model flowcharts. The steps required to define the construction tasks are described below.

Create an Estimate

Data describing the estimate were stored in the sample database in the "estimate" table, and they are shown in Table L.5. The piles considered in the estimate were defined in the "estimate_element" table, and are shown in Table L.6.

Select Repair Option

The repair option was selected from a list of options generated using the matrix shown in Figure 5.2(a). The repair option selected for the Gandy Bridge was an integral CP jacket with sacrificial anode.

Select Construction Modules

The construction modules were selected by applying the values provided by the decision matrix shown highlighted in Figure 5.5 to the module selection flowchart shown in Figure 5.4. The construction modules selected, shown highlighted in Figure 5.4, were the same as those discussed in Chapter V and included:

1. Pile access.
2. Concrete removal.
3. Reinforcement repair.
4. Continuity testing.
5. Continuity bonding.
6. Reference cell installation.

7. Formwork placement.
8. Grout casting.
9. Formwork removal.

As discussed in Chapter V, each construction module was represented by a flowchart that consisted of construction tasks arranged in sequential order and decision points that triggered the selection of the construction tasks based on inputs that were either defined by the user or retrieved from the Damage Assessment Model. If the data were not stored in the Damage Assessment Model, then the user was required to input the data.

Define Input Parameters Required by the Construction Module Flowcharts

Appendix L lists the input parameters used for the Gandy Bridge as required by each construction module.

Apply Knowledge Rules and Input Parameters

For each decision point in the construction module flowchart, there was a knowledge rule that determined the option selected by the decision point, which was called the “output” option. The knowledge rules were described in Appendix E.

Tables L.7 through L.16 list the output options selected for each decision point in the flowcharts for the Gandy Bridge.

Select Construction Task

Construction tasks were arranged in sequential order in the flowcharts and they were selected based on the output options at each decision point.

Stored Selected Construction Tasks in the Construction Process Model

The construction tasks selected for the Gandy Bridge were stored in the "estimate_task" table in the sample database, as shown in Table L.17. Figure 8.2 and 8.3 shows a report that was created using the data shown in Table L.17 for pile 2 on span 64. Figures L.1 to L.6 show reports that list the construction tasks required for pile 4 on span 116, pile 7 on span 238 and pile 6 on span 248. The reports were also created using the data listed in Table L.17.

CONSTRUCTION TASKS REQUIRED TO REPAIR A SPECIFIC BRIDGE ELEMENT

Estimate Description:	Install integral cathodic protection jackets with sacrificial anode mesh on 4 bridge piles of the Gandy Bridge
Bridge No.:	100300
Estimate No.:	100
Estimate Date:	6/3/2004
Bridge Element:	Prestressed concrete pile 2 on span 64
Pontis Condition State :	2

MODULE	**CONSTRUCTION TASK DESCRIPTION**
PILE ACCESS	Place floating protective barriers
PILE ACCESS	Access submerged pile using a platform
CONCRETE REMOVAL	Sound test concrete area
CONCRETE REMOVAL	Remove large pieces of unsound concrete
CONCRETE REMOVAL	Remove loose particles and remaining unsound concrete
CONCRETE REMOVAL	Dispose of debris
REINFORCEMENT REPAIR	Clean pile surface
CONTINUITY TESTING	Locate reinforcement position
CONTINUITY TESTING	Drill holes on concrete pile to expose reinforcement
CONTINUITY TESTING	Select base reinforcement
CONTINUITY TESTING	Measure potential difference between base reinforcement and others
CONTINUITY TESTING	Patch holes drilled in the concrete pile
CONTINUITY BONDING	Locate area of concrete to be removed
CONTINUITY BONDING	Saw cut concrete to make a small excavation
CONTINUITY BONDING	Remove concrete to make a small excavation
CONTINUITY BONDING	Connect continuity wires between existing pile reinforcement
CONTINUITY BONDING	Weld negative connection to transverse reinforcement
CONTINUITY BONDING	Cover welds with epoxy
CONTINUITY BONDING	Restore small excavations on pile surface to original profile
REFERENCE CELL INSTALLATION	Test reference cell
REFERENCE CELL INSTALLATION	Locate area of concrete to be removed
REFERENCE CELL INSTALLATION	Remove concrete to make a small excavation

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Figure 8.2 Report Generated Using Data Stored in the Construction Process Model for The Gandy Bridge, Page 1

MODULE	CONSTRUCTION TASK DESCRIPTION
REFERENCE CELL INSTALLATION	Install reference cell
REFERENCE CELL INSTALLATION	Restore small excavations on pile surface to original profile
FORMWORK PLACEMENT	Move formwork to working place
FORMWORK PLACEMENT	Measure bottom formwork position
FORMWORK PLACEMENT	Install bottom formwork
JACKET PLACEMENT	Mobilize jackets to bridge site
JACKET PLACEMENT	Move jacket to working place
JACKET PLACEMENT	Place jacket at proper elevation
JACKET PLACEMENT	Apply epoxy to jacket seams
JACKET PLACEMENT	Snap jackets together
JACKET PLACEMENT	Insert jacket fasteners
FORMWORK PLACEMENT	Install lateral formwork
FORMWORK PLACEMENT	Install lateral braces
GROUT MOBILIZATION	Mobilize grout truck to bridge site
GROUT MOBILIZATION	Mobilize grout pump to bridge site
GROUT MOBILIZATION	Quality control: slump test
GROUT MOBILIZATION	Quality control: strength cylinder casting
GROUT MOBILIZATION	Place grout hose at the bottom of the jacket
GROUT CASTING	Pump grout through a hose
GROUT CASTING	Remove grout hose
GROUT CASTING	Grout cast in jacket curing time
GROUT CASTING	Clean grout waste
FORMWORK REMOVAL	Remove bottom formwork
FORMWORK REMOVAL	Clean formwork
FORMWORK REMOVAL	Remove lateral braces
FORMWORK REMOVAL	Clean braces
FORMWORK REMOVAL	Remove lateral formwork
FORMWORK REMOVAL	Clean formwork
FORMWORK REMOVAL	Clean and form grout edges
PILE ACCESS	Remove floating protective barriers

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Figure 8.3 Report Generated Using Data Stored in the Construction Process Model for The Gandy Bridge, Page 2

8.5 Validation of the Parametric Quantity Model

The Parametric Quantity Model was used to calculate quantities for the construction tasks related to jacket placement. The author had not developed knowledge rules and equations for other construction tasks, which is recommended for future research since the methodology will be the same. The required parameters used by the model are shown in Table L.18; secondary parameters are shown in Table L.19.

It is important to note that the total number of piles in the contract was 239, and the cost estimated in the FDOT contract for the jackets on the Gandy Bridge were the same as those for the Howard Frankland Bridge, which was repaired in conjunction with the Gandy Bridge. The design plans listed the quantities estimated for the project by Parsons Brinckerhoff Quade & Douglas. These quantities were grouped under pay items designated by standard numbers defined by the FDOT. For the project under consideration, the quantity computation book was prepared by Parsons Brinckerhoff Quade & Douglas. The pay item for the integral CP jackets with sacrificial anodes was 2400-142-4. For the Gandy Bridge, pay item 2400-142-4 included eight jackets. According to the quantity computation book, four extra jackets were considered as a contingency. For the Howard Frankland Bridge, the number of jackets was increased by 25 percent as a contingency. The author had not developed a tool or gathered knowledge to define the number of extra jackets that should be considered as contingency items. Future research is recommended to account for contingency items in the Parametric Quantity Model.

The cost for each quantity item related to the jacket placement module, shown in Table 8.1, was calculated assuming that the total number of jackets in the project was 239. Thus, most costs shown in Table 8.1 were the same as those calculated for the example pile, which was one of the piles repaired at the Howard Frankland Bridge. For the Gandy Bridge, the cost per square foot of jacket (fiberglass and anode zinc mesh) was calculated as $901.14. This cost was slightly larger than that at the Howard Frankland Bridge because the piles at the Gandy Bridge were 20 inches wide. The piles at the Howard Frankland Bridge were 24 inches wide. As a result, the jackets at the Gandy Bridge were manufactured using a different mold than the one used for the jackets at the Howard Frankland Bridge, and the jacket fabrication cost was divided among a smaller number of piles.

Table 8.2 lists quantity items that were calculated by assuming that the total number of piles was four piles. Detailed calculations are shown in Appendix L. As shown in Table 8.2, the cost per jacket was $1776.42, which was 96 percent more than the cost calculated assuming that the total number of piles was 239 piles ($901.14). One of the reasons was that fixed costs associated with inspection of the jackets after installation were divided among four jackets instead of 239 jackets. Labor costs were also much higher because of the small number of jackets installed. In general, the model estimated labor costs as the larger of either one man-day or the number of man-days calculated as one percent of the total footage of jackets as discussed in Chapter H. For the Gandy Bridge, the number of man-days calculated as one percent of the total footage of jackets was smaller than one man-day. Thus, one-man day was the number of man-days considered, and it was evenly divided among four jackets.

The tendency to increase the price because of a smaller number of jackets, as shown by the results on Table 8.2 and 8.1, was observed in FDOT Project 7007-3506 in which the price per jacket was $1,613 and the total number of jackets was eight jackets (Corrpro 1999).

Table 8.1 Costs for Quantities Associated with the Jacket Placement Module for the Gandy Bridge (4 piles of 239)

Quantity Item	Unit	Quantity	Unit Cost	Cost Per Jacket
Jacket fiberglass	ft^2	50	$6.39	$319.50
Jacket zinc anode mesh	ft^2	50	$4.39	$219.5
Standoff	each	32	$0.10	$3.20
Longitudinal seam epoxy	gallon	0.3	$6.67	$2.01
Transverse seam epoxy	gallon	0.0	$6.67	$0.00
Jacket fasteners	each	36	$0.24	$8.64
Jacket fabrication	lump sum	1	$610.00	$152.5
Labor, senior technician	man-day	14	$450.00	$26.35
Labor, worker	man-day	14	$150.00	$8.79
CP Specialist inspection	lump sum	1	$2,500.00	$10.46
Subtotal:				$750.95
Mark up (20 %):				$150.19
Total Cost:				$901.14

Table 8.2 Costs for Quantities Associated with the Jacket Placement Module for the Gandy Bridge (4 piles of 4)

Quantity Item	Unit	Quantity	Unit Cost	Cost per Jacket
Jacket fiberglass	ft^2	50	$6.39	$319.50
Jacket zinc anode mesh	ft^2	50	$4.39	$219.5
Standoff	each	32	$0.10	$3.20
Longitudinal seam epoxy	gallon	0.3	$6.67	$2.01
Transverse seam epoxy	gallon	0.0	$6.67	$0.00
Jacket fasteners	each	36	$0.24	$8.64
Jacket fabrication	lump sum	1	$610.00	$152.50
Labor, senior technician	man-day	1	$450.00	$112.50
Labor, worker	man-day	1	$150.00	$37.50
CP Specialist inspection	lump sum	1	$2,500.00	$625.00
Subtotal:				$1480.35
Mark up (20 %):				$296.07
Total Cost:				$1776.42

The cost of the CP system was listed in the design plans under FDOT pay item 2400-142-4 as $450.00 per square meter of jacket. The total jacket quantity was listed as 1,193.7 square meters for the 239 jackets. FDOT pay item 2400-14-2 included costs associated with continuity testing, continuity correction, jacket placement, grout casting and formwork. According to expert knowledge (Mather 2004), the cost of the CP system excluding continuity testing, continuity correction, grout casting and formwork was approximately 40 percent of the cost listed under pay item 2400-142-4. . Thus, the cost per jacket given by FDOT quantities was defined as follows:

$$\frac{\$450.00 \cdot 1193.7\ \mathrm{m}^2 \cdot 0.40}{239\ \text{Jackets}} = \$899.0\ \text{per jacket}$$

The cost per jacket given by the FDOT pay item ($899) was about 0.2 percent higher than the cost estimated by the model ($901.14) assuming that the total number of jackets was 239 jackets.

One of the deficiencies of the quantity computation book noted by the author was that the cost of restoring spalled areas and repairing reinforcing was incomplete. The cost of restoring spalled areas and repairing reinforcing was accounted by pay items 2401-70-4 and 2415-1-4, respectively. In the project under consideration, pay items should include quantities for the concrete piles, beams and footings. However, the quantity computation book showed that for the Gandy Bridge these pay items included only quantities corresponding to beams and footings (FDOT (n)). Quantities for the piles were left out. Conversely, for the Howard Frankland Bridge, the above pay items included quantities for piles, beams and footings as was expected (FDOT (n)). Thus, the author concluded that pile costs associated to restoring spalled areas and repairing reinforcing should also have been included for the Gandy Bridge, but were mistakenly left out.

FDOT pay item 2455-81-01 described as “Cathodic Protection – F&I Zinc Anodes” referred to the additional bulk zinc anode installed in the Jacket. FDOT pay item 2457-70-35 “Integral Pile Jacket – Structural” was a contingency item assumed by the design engineer (FDOT (o)).

8.6 Conclusions

As demonstrated by the results of the above queries, detailed inspection data could be stored and retrieved from the Damage Assessment Model as needed.

By comparing the construction tasks selected by the Construction Process Model to those required by FDOT project plans, it was concluded that the Construction Process Model was able to define the construction tasks required to repair bridge piles at the pre-design stage with a level of detail similar to or higher than that provided by the FDOT project plans.

Cost estimates by the Parametric Quantity Model for the quantity items associated with jacket placement were about 0.2 percent higher than the cost given by FDOT if the actual number of piles were considered. The actual number of piles included those in the Gandy Bridge as well as those in the Howard Frankland Bridge, which were repaired simultaneously.

If the number of piles considered where only those at the Gandy Bridge, the cost estimated by the Parametric Quantity Model was 96 percent higher than the cost given by FDOT because fixed costs were divided among a smaller number of jackets. This latter case was a hypothetical case study, and it did not reflect the actual project data. Nevertheless, such a case study was included to demonstrate that the number of piles being repaired was the main cost driver.

Costs calculated by the Parametric Quantity Model were based on data available at the pre-design stage and were compared to those estimated by the FDOT after 100 percent of the design was completed.

CHAPTER IX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary

A Damage Assessment Model, Construction Process Model and Parametric Quantity Model were developed with the purpose of capturing the engineering knowledge involved in the MLE estimating process of bridge repair construction projects.

The Damage Assessment Model was used to maintain detailed bridge inspection data in an electronic format compatible with the existing Pontis™ database. Detailed inspection data, which provided quantitative values for the different damage types observed in bridges, were stored in a sample database that was developed using the entity-relationship model defined in the Damage Assessment Model. Detailed inspection data were retrieved from the database, so that data could be used as either input parameters in the knowledge rules that triggered the selection of construction tasks in the Construction Process Model or data could be used as variables in the equations used to estimate quantities in the Parametric Quantity Model.

The Construction Process Model was used to incorporate the logic behind the construction process for different repair methods. The Construction Process Model was composed of seven repair matrices that defined specific repair methods for each Pontis™ bridge element. Construction tasks were grouped in construction modules that were modeled as flowcharts. Each construction module flowchart was composed of construction tasks arranged in sequential order and decision points that triggered the selection of construction tasks based on input parameters and knowledge rules. Input parameters were provided by the user, retrieved from the model or pre-defined in the model by expert knowledge. Specifically, twelve construction modules were developed. Input parameters and knowledge rules related to the latter construction modules were also defined. The construction modules developed involved construction tasks related to the repair of concrete bridge piles that were damaged due to reinforcement corrosion and related concrete deterioration.

Data describing the construction tasks that were considered in the construction module flowcharts were modeled using the entity-relationship model and were stored in the sample database described previously. Such data were retrieved from the sample database because they were required by the Parametric Quantity Model in order to select the MLE quantity items that had to be estimated for the construction tasks selected.

The Parametric Quantity Model combined data generated by the Damage Assessment Model and the Construction Process Model with additional expert knowledge and parameters into equations that were used to estimate MLE quantities. Parameters were variables used in the equations. Parameters were classified either as required parameters or secondary parameters. Required parameters had to be input by the user. Secondary parameters could be either default values (defined in the model), or they could be user defined. In most cases, default values used in the model were based on the most common value observed in past repair projects, and such default values were confirmed by expert knowledge. In a few cases, there were not historical data to characterize a default value, so expert knowledge was used as the sole basis to define the default value.

Specifically, equations, parameters, and knowledge rules used to estimate MLE quantities related to CP jackets were developed and tested.

To compliment the research, the author investigated the use of neural networks as a tool to predict actual damage in bridge piles, conducted a survey to define labor productivity factors, and collected data to define the duration of construction activities related to bridge repair.

Detailed inspection data defining the dimensions of spalls observed above water in concrete piles located in a marine environment in Florida were used as input parameters in neural networks in order to predict the actual volume of deteriorated concrete removed from such piles. Detailed inspection data defining the crack length and class (width) along with spall dimensions were used to estimate the probability of having to replace stirrups in the pile. The number of faces and corners on a bridge pile that showed deterioration were also used to estimate the probability of having a given number of longitudinal mild steel reinforcing bars with more than 25 percent cross section loss.

A preliminary survey to define factors that affect labor productivity on bridge repair construction activities was conducted among Navy divers, who are regarded as knowledge experts. The effect of water current, visibility, water temperature and water pressure were investigated. The experts were asked to validate the ranges used by the author to characterize the water current, visibility, water temperature and water pressure, or to define a better range if they did not agree with the ranges proposed. The divers were asked to provide a productivity factor for each range defined and also to estimate the duration of underwater construction tasks.

A study aimed at collecting duration data for construction activities on bridge piles was conducted while observing the repair of bridge piles in Melbourne, Florida during an eight-week period.

9.2 Conclusions

The data modeling presented in the Damage Assessment Model proved that detailed inspection data could be stored in a database that was compatible with the existing Pontis™ database maintained by the FDOT. Such data modeling associated quantitative damage values with each Pontis™ condition state definition. The data could be retrieved and manipulated using SQL queries created with Microsoft® Access (2000) and used in the decision process required to select construction tasks and to estimate MLE quantities for bridge repair projects. Specifically, Pontis™ Condition State definitions provided only a qualitative description of the damage existing in the bridge such as:

> "Delaminations, spalls, and corrosion of non-prestressed reinforcement are prevalent. There may also be exposure and deterioration of the prestressed system (manifested by loss of bond, broken strands or wire, failed anchorages, etc). There is sufficient concern to warrant an analysis to ascertain the impact on the strength and/or serviceability of either the element or the bridge" (AASHTO 1997)."

While the experimental data relate specifically to FDOT, the research findings and conclusions may be extended to all states that use Pontis™ because each collects and maintains inspection data based on nationwide guidelines set to "increase uniformity and consistency of inspections" (Hartle et al. 1990).

The Construction Process Model could be used to define construction tasks required for the repair of bridge piles. Specifically, construction tasks defined included repairing deteriorated concrete and steel reinforcing as well as installing an integral CP jacket. Using the new methodology, it was possible to define construction tasks and MLE quantities without using 100 percent complete design documents. The data used to define construction tasks was available at the pre-design stage. Still, the construction tasks selected by the Construction Process Model were defined with a level of detail similar or higher than that provided by project plans after 100 percent of the design was completed.

Including construction process and site conditions in the development of an early estimate most likely will improve its accuracy. Oberlender (2001) developed a scoring procedure to determine the accuracy of an estimate based on factors driving the estimate's accuracy. Even though results reported by Oberlender referred to industrial process facilities, they are significant to this research because they addressed the importance of including the construction process and site conditions in an early estimate. According to Oberlender (2001), the most important driver of estimate accuracy was the "basic process design," which accounts for 25 percent of the estimate score. He concluded that:

> "A comprehensive and definitive process design is crucial to the accuracy of an early estimate of an industrial process facilities. Identifying the site requirements of a project is also important for estimate accuracy. The site requirements factor accounts for 12.4% of the estimate score."

Several efforts to determine unit costs for Pontis™ MR&R actions are described in the literature, but none of them addressed the unique physical condition of a given bridge element and the construction process and tasks that are required to repair the bridge element. Cobbs (1995) described a methodology that defined unit costs for Pontis™ MR&R actions by collecting historical contract data and expert data. However, his results showed large standard deviations for maintenance, repair and rehabilitation costs for some bridge elements.

As stated by Smith (1999), cost of bridge maintenance should not be based on average values obtained from historical data since “this practice can induce serious errors because it does not consider that many costs are related to the physical and characteristics of the bridge.”

In contrast, the new methodology provided MLE quantities that correspond to construction tasks selected by the Construction Process Model given the unique physical condition of the bridge. MLE quantities could be applied against current cost data to determine the cost of repairing a bridge element.

In addition, specific repair options for each bridge element on a Pontis™ Condition State could be defined instead of the generic Pontis™ Condition State Definition. Specifically, typical Pontis™ MR&R actions for a prestressed concrete pile (element 226) in Pontis™ Condition State 4 were “do nothing, rehab unit, or replace unit”(AASHTO 1997).

The cost estimated by the Parametric Quantity Model for a CP jacket with a sacrificial anode using only the data available at the pre-design stage was within 11 percent of the cost that was estimated by the engineers after the 100 percent design plans were completed. The accuracy of the estimate was defined as the percent difference between the engineer’s estimate and the estimated value by the model. A major factor that affected the cost of the jackets was the number of piles that were repaired, since these fixed costs were independent of the number of piles repaired. As the number of piles being repaired increased, these costs were evenly divided among a larger number of piles; thus, reducing the cost per pile.

According to the Association for the Advancement of Cost Engineering (1997), the expected accuracy range for an estimate based on 0 to 2 percent project definition may have an accuracy of +100/-50 percent assuming that the accuracy of an estimate with 100 percent project definition is +10/-5 percent (AACE 1997). While the expected accuracy of bridge repair projects that are based on 100 percent project definition is not clearly defined in the literature, there are indications that such a value most likely is +10/-5 as discussed below.

Based on a URS cost database, a multidisciplinary civil engineering firm, the average percent difference between the low bid and URS engineer's estimate for highway projects was 13.6 percent. Such an average was based on 123 projects that totaled a $473,005,451 low bid value and a $497,691,557 engineer's estimate value. When comparing URS engineer's estimate to the average of the three lowest bids, the percent difference was less than 1 percent. Generally, URS engineer's estimates were based on 90 to 100 percent project definition (Cabage 2005).

According to Anderson (1997), several states have set guidelines to improve the accuracy of the cost estimates. As an example, Maryland set a goal that estimates "differed from the final costs by no more than 10 percent." To fulfill such a goal, Maryland includes a 35 to 40 percent contingency.

The accuracy of the model was better than the accuracy of cost estimating models for highway projects described in the literature. Bell (1987) reported a cost estimating regression analysis model used to estimate the cost of bridge replacement that requires a single input parameter, the bridge substructure concrete volume. Such a model had an accuracy of 22%. Other cost estimating models created by Bell for highway projects had accuracies within the range of +/-17 to +/-35 percent.

The analysis of damage data from detailed inspection reports demonstrated that the data, which described concrete deterioration, that is spall width, length and depth as well as crack length, showed defined normal distributions for each Pontis™ Condition State. Therefore, it was possible to define damage default values for each Pontis™ Condition State using quantitative terms, based on the mean values and ranges observed for each damage parameter. The analysis of detailed inspection data and as-built data also demonstrated that actual damage quantities were larger than those defined by detailed inspection data.

Neural networks and probability trees were combined into dynamic probability trees to estimate actual damage quantities from detailed inspection reports. Such dynamic probability trees were a tool to estimate actual damage quantities based on inspection data, specifically volume of concrete to be removed, and both transverse and longitudinal reinforcement replacement due to corrosion damage. The available data used by the neural network were limited and referred to individual bridges. Also, the data referred only to damage above the water. Nevertheless, the results obtained when testing the neural network on each individual bridge were acceptable. Testing the neural network with a data set different from the data sets used to train the network validated the neural networks.

The neural network results were encouraging, although they could not be generalized for other bridges because they were developed from a very small amount of data that referred to single bridges.

9.3 Limitations of Research

The research neither analyzed nor included contingency values. Stevenson (1984) identified the following source of contingency: pricing, scope omission and error; escalation forecasts, schedule changes, expansion of scope, and acts of God.

The neural networks that predicted the actual damage data from detailed inspection data most likely would not be applicable to other bridges, since the neural networks were trained with a limited set of data due to the lack of historical as-built data. The results that were provided by the neural network to determine the number of stirrups to be replaced in a bridge were not reliable, because the neural network failed to identify the cases in which stirrup replacement were not required. The neural networks that were used to determine the actual amount of concrete to be removed and the number of longitudinal bars with more than 25 percent cross section loss provided good results.

The researcher used a deterministic approach while utilizing detailed inspection data from a given bridge, but she did not analyze the reliability of the inspection data.

9.4 Future Research

The following six recommendations are given for future research:

1. Define the logic involved in the construction process of repair methods not included in this research, as well as the construction tasks, knowledge rules and input parameters for such repair options. Implement a probabilistic tool to select construction tasks, which are dependent on probabilistic parameters. Implement a tool that allows grouping piles for which construction activities are common. Incorporate user defined damage location into the knowledge rules used in the Construction Process Model.
2. Implement the Damage Assessment Model, Construction Process Model and Parametric Quantity Model into an automated software system. Provide a user-friendly interface to input the data required by the models.
3. Future research is recommended to collect and analyze data for damage below water. Results presented in this chapter allowed the characterization of concrete spall parameters for each Pontis™ Condition State above and below water (MLW). However, the crack damage data referred only to damage located above water.
4. Collect as-built data. Use the new as-built data to train and test the neural networks proposed on a greater sample.
5. Conduct a second survey on a larger sample of divers and other bridge construction workers to determine factors affecting labor productivity.
6. Collect unit prices specific to bridge repair construction activities.

APPENDIX A

SAMPLE BRIDGE INSPECTION REPORTS AND AS-BUILT REPORTS

Data used by the Damage Assessment Model were collected from detailed inspection reports and as-built reports prepared by the FDOT. Inspection reports described the damage observed before the bridge was repaired. The actual amount of damage was recorded on as-built reports after the repair was finished. Both, inspection reports and as-built reports are not releasable since 9/11/2001 based on Florida Statute 119.07 (3)(ee). Pictures are on file in researcher's office and FDOT.

An inspection report of the Howard Frankland, conducted on September 30, 1998, included above and below water inspection data. The bridge inspection report data included the damage data for pile 6 on span 6 (FDOT (b)), pile 1 on span 52 (FDOT (c)), pile 3 on span 13 and pile 8 on span 12 (FDOT (d)), which were used in the examples discussed in Chapter IV, V and VI.

As-built reports used in the research corresponded to bridge pile repairs conducted on the Mathew Bridge (FDOT (e)) and the bridges over Haulover Creek (FDOT (f)), San Pablo River (FDOT (g)), and Broward River (FDOT (h))

APPENDIX B

DAMAGE ASSESSMENT MODEL QUERIES

Appendix B presents the structured query language (SQL) codes called “queries” that were developed by the author to retrieve data stored in the Damage Assessment Model. The queries were implemented using Microsoft® Access (2000). The purpose of the queries was discussed in Chapter IV. Query B.1 was discussed in Example 4.1. The Microsoft® Access Report Wizard used to generate the report shown in Figure 4.7 was also discussed in Example 4.1. Query B.2 and Query B.3 were discussed in Examples 4.2 and 4.3. The results of the latter queries were also shown in Examples 4.2 and 4.3.

Microsoft® Access Wizard

Figure B.1 shows the Microsoft® Access code used to create a report that listed all damage data stored in the Damage Assessment Model for a given bridge. The report was created from the data retrieved using Query B.1.

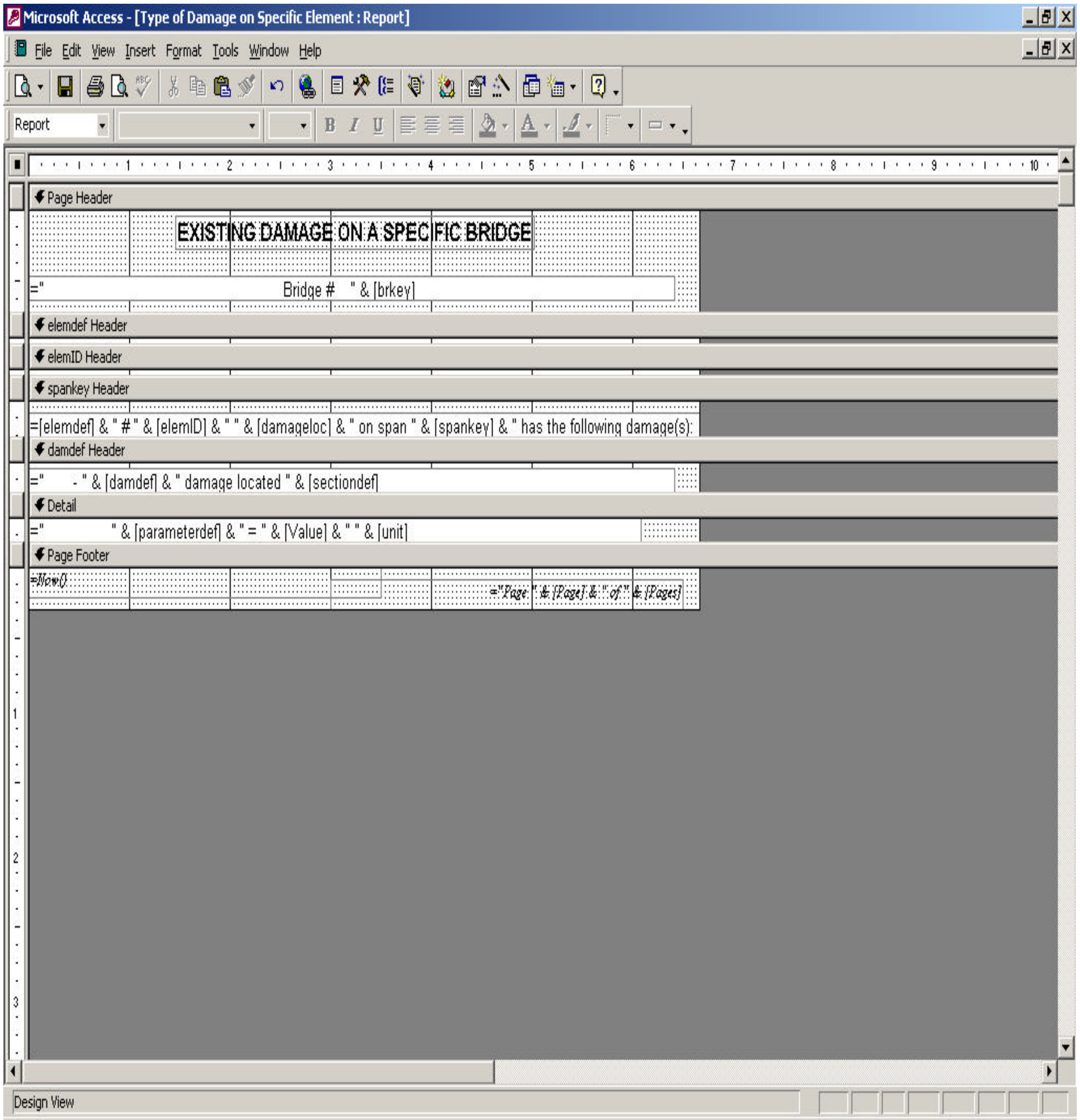

Figure B.1 Microsoft® Access Report Wizard Used to Create the Report Shown in Figure 4.7

Query B.1

```
SELECT DISTINCTROW damage.brkey, damage.spankey, elementdef.elemdef,
                   damage.elemID, damagedef.damdef,
                   parameterdef.parameterdef, damage.value,
                   damage.unit, damage.damageloc, sectiondef.sectiondef
FROM
    sectiondef INNER JOIN
        (parameterdef INNER JOIN
            (elementdef INNER JOIN
                (damagedef INNER JOIN damage
                ON (damagedef.damID = damage.damID) AND
                    (damagedef.elemkey = damage.elemkey))
            ON elementdef.elemkey = damage.elemkey)
        ON (parameterdef.parameterID = damage.parameterID) AND
            (parameterdef.damID = damage.damID) AND
            (parameterdef.elemkey = damage.elemkey))
    ON (sectiondef.i = damage.i) AND
        (sectiondef.elemkey = damage.elemkey)
WHERE (((damage.brkey)=[ENTER BRIDGE #]));
```

Query B.1 Results

Table B.1 Data Retrieved by Query B.1

brkey	***spankey***	***elemdef***	*elemID*	*damdef*	*parameterdef*	*value*	*unit*	*damageloc*	*sectiondef*
150107	6	Prestressed concrete pile	6	Spall	spall length	39	inch	E	above MLW
150107	6	Prestressed concrete pile	6	Spall	spall depth	4	inch	E	above MLW
150107	6	Prestressed concrete pile	6	Spall	spall width	20	inch	E	above MLW
150107	6	Prestressed concrete pile	6	Longitudinal reinforcement corrosion	reinforcement cross section loss	100	percent	E	above MLW
150107	12	Prestressed concrete pile	8	Spall	spall length	16	inch	SE	below MLW (0 ft to -3 ft)
150107	12	Prestressed concrete pile	8	Spall	spall depth	1	inch	SE	below MLW (0 ft to -3 ft)
150107	12	Prestressed concrete pile	8	Spall	spall width	6	inch	SE	below MLW (0 ft to -3 ft)
150107	13	Prestressed concrete pile	3	Spall	spall length	43	inch	E	below MLW (-3 ft or more)
150107	13	Prestressed concrete pile	3	Spall	spall depth	3	inch	E	below MLW (-3 ft or more)
150107	13	Prestressed concrete pile	3	Spall	spall width	16	inch	E	below MLW (-3 ft or more)
150107	13	Prestressed concrete pile	3	Longitudinal reinforcement corrosion	reinforcement cross section loss	100	percent	E	below MLW (-3 ft or more)
150107	52	Prestressed concrete pile	1	Crack	crack class	2	class	NW	above MLW
150107	52	Prestressed concrete pile	1	Crack	crack length	47	inch	NW	above MLW

Query B.2

```
SELECT DISTINCTROW damage.elemID, damage.spankey, elementdef.elemdef,
                   element.stkey, damagedef.damdef,
                   parameterdef.parameterdef, damage.value, damage.unit
FROM  sectiondef INNER JOIN
      ((elementdef INNER JOIN element
            ON elementdef.elemkey = element.elemkey) INNER JOIN
                  (damagedef INNER JOIN
                        (parameterdef INNER JOIN damage
                        ON (parameterdef.parameterID = damage.parameterID)
                           AND (parameterdef.damID = damage.damID) AND
                           (parameterdef.elemkey = damage.elemkey) AND
                           (parameterdef.damID = damage.damID))
                  ON (damagedef.damID = damage.damID) AND
                     (damagedef.elemkey = damage.elemkey))
            ON (elementdef.elemkey = damage.elemkey) AND
               (element.elemID = damage.elemID) AND
               (element.spankey = damage.spankey) AND
               (element.elemkey = damage.elemkey) AND
               (element.brkey = damage.brkey))
      ON (sectiondef.i = damage.i) AND
         (sectiondef.itype = damage.itype) AND
         (sectiondef.elemkey = damage.elemkey)
GROUP BY   damage.elemID, damage.spankey, elementdef.elemdef,
           element.stkey, damagedef.damdef, parameterdef.parameterdef,
           damage.value, damage.unit, damage.brkey, damage.elemkey,
           damage.damID, damage.parameterID
HAVING (((damage.elemID)=[Enter Element ID]) AND
        ((damage.spankey)=[Enter Span]) AND
        ((damage.brkey)=[Enter bridge #]) AND
        ((damage.elemkey)=[Enter Element Type]) AND
        ((damage.damID)=[Enter Damage ID]) AND
        ((damage.parameterID)=[Enter Parameter ID]));
```

Query B.3

```
SELECT [Damage Table].brkey, [Damage Table].elemID, [Damage Table].spankey,
        [Damage Table].damageloc, [Damage Table].[spall depth],
        [Damage Table].[spall length], [Damage Table].[spall width],
        ([spall depth]*[spall length]*[spall width]) AS plan

FROM [Damage Table]

WHERE ((([Damage Table].brkey)=150107) AND
        (([Damage Table].elemID)=6) AND
        (([Damage Table].spankey)=6) AND
        (([Damage Table].damID)=1));
```

APPENDIX C

REPAIR MATRICES

From a project level perspective, the Maintenance, Repair and Rehabilitation (MR&R) options provided by Pontis™ were poor since they did not specify a repair method. To overcome such a pitfall, seven repair matrices were developed which related specific repair methods to each element in the Pontis™ database. Such repair matrices included Pontis™ elements and repair methods that were outside the scope of this research. However, they were developed to provide a "big picture" of the model by defining the cases that should be considered in order to include all Pontis™ elements with their respective repair options. In the repair matrices, the vertical axis corresponded to the Pontis™ element and the horizontal axis, to the repair methods. The intersection of a horizontal axis with a vertical axis, could take a value equal to either "1" or "0". If the value shown was "1", the repair method listed in the vertical axis applied to the element listed in the horizontal axis. If the value was "0", the repair method did not apply to the element. Proceeding each matrix, there is a table describing the Pontis™ elements used in each matrix as defined in Pontis™.

Table C.1 Description of Concrete Elements Used by Pontis™

Pontis Item	CoRe Element (Pontis) Description	NBI Item Number	NBI Item Description	Material
12	Concrete deck – bare (EA)	58	Deck	Concrete
26	Concrete deck – protected with coated bars (EA)			
27	Concrete deck – protected with cathodic system (EA)			
38	Concrete slab – bare (EA)			
52	Concrete slab – protected with coated bars (EA)			
53	Concrete slab – protected with cathodic system (EA)			
13	Concrete deck – unprotected with AC* overlay (EA)			
14	Concrete deck – protected with AC* overlay (EA)			
39	Concrete slab – unprotected with AC* overlay (EA)			
40	Concrete slab – protected with AC* overlay (EA)			
18	Concrete deck – protected with rigid overlay (EA)			
22	Concrete deck – protected with rigid overlay (EA)			
44	Concrete slab – protected with rigid overlay (EA)			
48	Concrete slab – protected with rigid overlay (EA)			
104	P/S Concrete – closed web/box girder (m)	59	Superstructure	Prestressed Concrete
109	P/S Concrete – open girder/beam (m)			
115	P/S Concrete – stringer (stinger- floor beam system) (m)**			
143	P/S Concrete – arch (m)			
154	P/S Concrete – floor beam (m)			
105	Reinforced concrete – closed web/box girder (m)	59	Superstructure	Concrete
110	Reinforced concrete – open girder/beam (m)			
116	Reinforced concrete – stringer (stringer–floor beam system(m)**			
144	Reinforced concrete – arch (m)			
155	Reinforced concrete – floor beam (m)			
204	P/S Concrete – column or pile extension (EA)	60	Substructure	Prestressed Concrete
226	P/S Concrete – submerged pile (EA)			
233	P/S Concrete – cap (EA)			
205	Reinforced concrete – column or pile extension (EA)	60	Substructure	Concrete
210	Reinforced concrete – pier wall (m)			
215	Reinforced concrete – abutment (m)			
220	Reinforced concrete – submerged pile cap/footing (EA)			
227	Reinforced concrete – submerged pile (EA)			
234	Reinforced concrete – cap (m)			
241	Reinforced concrete culvert (along length of barrel) (m)	61	Culvert	Prestressed Concrete

(Hearn et al. 1997, pp5, Figure 2. Figure was Modified)

* Asphalt is not considered a protection for concrete bridges, but it provides a smooth riding surface.
** Stringers may exist in a bridge without a stringer-floor beam system.

Table C.2 Concrete Element Repair Matrix

Pontis Item	Portland cement mortar patches	Portland cement concrete patches	Latex modified cement mortar patches	Latex modified cement concrete patches	Polymer patches	Polymer mortar patches	Polymer concrete patches	Proprietary product – self leveling patches	Proprietary product – high early strength patches	Proprietary product – non shrink grout patches	Asphalt patches	Shotcrete patches	Portland cement concrete overlays	Latex modified cement concrete overlays	Epoxy concrete overlays	Methyl methacrylate concrete overlay	Asphalt overlay/paving*	Asphalt removal	Conductive bitaminous overlay	Epoxy injection	Epoxy resin coatings	Add/replace reinforcement – fiberglass composite strips	Add/replace reinforcement – carbon fiber composite strips	Add/replace reinforcement – external post-tensioned FRP	Add/replace reinforcement – internal ungrouted post-tensioned FRP	Add/replace reinforcement – internal grouted post-tensioned FRP	Add/replace reinforcement – external post-tensioned steel strands	Add/replace reinforcement – internal ungrouted post-tensioned steel strands	Add/replace reinforcement – internal grouted post-tensioned steel strands	Add/replace reinforcement – external post-tensioned steel rebar	Add/replace reinforcement – internal ungrouted post-tensioned steel rebar
12	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1
26	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1
38	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1
52	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1
53	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1
39	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1
44	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1
48	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1
104	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
109	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
115	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
143	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
154	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
105	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
110	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
116	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
144	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
155	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
204	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
226	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
233	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
205	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
210	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
215	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
220	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
227	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
234	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
241	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1

Table C.2 (Continued)

Pontis Item	Add/replace reinforcement – internal grouted post-tensioned steel rebar	Add/replace reinforcement – fiberglass composite wraps	Add/replace reinforcement – carbon fiber composite wraps	Add/replace reinforcement – steel rebar cage	Add/replace reinforcement- - lap weld rebar	Add/replace reinforcement– wire mesh	All polymer encapsulation jacket	Integral cathodic protection jacket with sacrificial anode mesh	Integral cathodic protection jacket with titanium impressed current anode	Encapsulation with removable form or jacket	Hybrid fiber epoxy composites	Electrochemical removal of chlorides	Waterproofing membranes	Asphalt waterproofing membrane	Continuous titanium impressed current mesh embedded in concrete	Concrete removal – saw cut	Concrete removal – chipping hammer	Concrete removal – scabbler	Concrete removal – scarifier	Concrete removal/cleaning – sandblaster	Concrete removal/cleaning – water jet	Concrete removal/cleaning – air jet	Concrete cleaning – detergents, chemicals	Steel cleaning – sandblaster	Steel cleanning – wire brush/drill
12	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
26	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
38	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
52	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
53	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
39	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
44	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
48	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
104	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
109	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
115	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
143	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
154	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
105	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
110	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
116	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
144	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
155	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
204	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
226	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
233	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
205	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
210	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
215	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
220	1	1	1	1	1	1	0	0	0	0	1	0	1	0	0	1	1	0	0	1	1	1	0	0	1
227	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
234	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
241	1	1	1	1	1	1	0	0	0	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1

Table C.3 Description of Steel Elements Used by Pontis™

Pontis Item	CoRe Element (Pontis) Description	NBI Item Number	NBI Item Description	Material
28	Steel – open grid deck (EA)	57	Deck	Steel
29	Steel – concrete filled grid deck (EA)			
30	Steel – corrugated/ orthotropic/ etc. deck (EA)			
101	Steel unpainted – closed web/box girder (m)	58	Superstructure	Unpainted Steel
106	Steel unpainted – open girder/beam (m)			
112	Steel unpainted – stringer (stringer – floor beam system) (m)*			
120	Steel unpainted – through truss (bottom chord) (m)			
125	Steel unpainted – through truss (excluding bottom chord) (m)			
130	Steel unpainted – deck truss (m)			
140	Steel unpainted – arch (m)			
151	Steel unpainted – floor beam (m)			
146	Cable uncoated – cable (not embedded in concrete) (EA)			
160	Steel unpainted – pin and/or pin and hanger assembly (EA)			
	Steel unpainted – diaphragm (m) **			
102	Steel painted – closed web/box girder (m)	58	Superstructure	Painted Steel
107	Steel painted – open girder (m)			
113	Steel painted – stringer (stringer – floor beam system) (m)*			
121	Steel painted – through truss (bottom chord) (m)			
126	Steel painted – through truss (excluding bottom chord) (m)			
131	Steel painted – deck truss (m)			
141	Steel painted – arch (m)			
152	Steel painted – floor beam (m)			
147	Cable uncoated – cable (not embedded in concrete) (EA)			
161	Steel painted – pin and/or pin hanger assembly (EA)			
	Steel painted – diaphragm (m) **			
201	Steel unpainted – column or pile extension (EA)	59	Substructure	Unpainted Steel
225	Steel unpainted – submerged pile (EA)			
230	Steel unpainted – cap (m)			
202	Steel painted – column or pile extension (EA)	59	Substructure	Painted Steel
231	Steel painted – cap painted (m)			
240	Steel unpainted – culvert (along length of barrel) (m)	61	Culvert	Unpainted Steel

(Hearn et al.1997, pp5, Figure 2. Figure was Modified)

* Stringers may exist in a bridge without a stringer-floor beam system.
** There is not a CoRe element that corresponds to diaphragms. However, since diaphragms are primary members in curved bridges, this table includes diaphragms.

Table C.4 Steel Element Repair Matrix

Pontis Item	Solvent cleaning	Hand-tool cleaning	Power-tool cleaning	Brush-off blast	Sandblast	Pressurized water blasting	Wet abrasive blasting	Vacuum blasting	Novel cleaning methods	Coating – inhibitive system	Coating – zinc-rich system	Coating – barrier system	Metallizing	Fatigue crack – drill a stophole at the crack tip	Fatigue crack – weld toe grinding	Fatigue crack – toe crack grinding	Fatigue crack – full penetration groove weld	Fatigue crack – high strength bolted splice plates	Add cover plates	Add stiffener
28	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0
29	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0
30	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0
101	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
106	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
112	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
120	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0
125	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0
130	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0
140	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0
151	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
146	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
160	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
102	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1
107	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
113	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
121	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0
126	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0
131	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0
141	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0
152	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
147	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
161	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
201	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
225	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
230	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
202	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
231	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
240	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0

Table C.4 (Continued)

Pontis Item	Add double side plates	Add side plates	Add member	Remove member	Add/replace rivets	Add/replace bolts	Add/replace welda	Add/replace connecting angles	Add adjustable bars	Add center truss	Add double truss	External post-tensioned – steel rebar	External post-tensioned – steel strands	External post-tensioned – FRP	Straightening – thermal expansion/contraction	Flame straightening	Hot straightening	Cold straightening	Cathodic protection – sacrificial anodes	Cathodic protection impressed current anodes
28	0	0	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	1	1
29	0	0	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	1	1
30	0	0	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	1	1
101	1	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1
106	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1
112	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1
120	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
125	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
130	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
140	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1
151	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1
146	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
160	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
102	1	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1
107	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1
113	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1
121	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
126	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
131	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
141	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1
152	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1
147	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
161	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
201	0	0	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	1	1
225	0	0	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	1	1
230	0	0	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	1	1
202	0	0	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	1	1
231	0	0	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	1	1
240	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1

Table C.5 Description of Timber Elements Used by Pontis™

Pontis Item	CoRe Element (Pontis) Description	NBI Item Number	NBI Item Description	Material
31	Timber deck – bare (EA)	58	Deck	Timber
54	Timber slab – bare (EA)			
32	Timber deck – protected with AC overlay (EA)			
55	Timber slab – protected with AC overlay (EA)			
111	Timber – open girder/beam (m)	59	Superstructure	Timber
117	Timber – stringer (stringer –floor beam system) (m)			
135	Timber – truss/arch (m)			
156	Timber – floor beam (m)			
206	Timber – column or pile extension (m)	60	Substructure	Timber
216	Timber – abutment (m)			
228	Timber – submerged pile (EA)			
235	Timber – cap (m)			
242	Timber – culvert (along length of barrel) (m)	61	Culvert	Timber

(Hearn et al.1997, pp5, Figure 2. Figure was Modified)

Table C.6 Timber Element Repair Matrix

Pontis Item	Asphalt overlay (wearing surface)	Geotextile fabrics	Bituminous roofing cement filler	Stress laminating – external steel rods	Stress laminating – internal steel rods	Drainage installation	Wood cleaning – brushing	Wood cleaning – water jet	Surface treatment – liquid preservative	Surface treatment – semisolid preservative	Surface treatment – liquid fumigant	Surface treatment – solid fumigant	Member augmentation – splicing- wood plates	Member augmentation – splicing – steel plates	Member augmentation – scabbing – wood plates	Clamping	Stitching	Concrete jacket	All polymer encapsulation	Pile posting – (complete section replacement)	Pile restoration – (wedge-shaped section replacement)	Pile wrapping	Epoxy injection of cracked and split members (truss joints)	Epoxy injection and reinforcement of decayed wood	Epoxy grouting	Member replacement
31	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
54	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
32	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
55	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
111	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
117	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
135	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
156	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
206	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
216	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
228	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
235	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
242	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1

Table C.7 Description of Bearing Elements Used by Pontis™

Pontis Item	CoRe Element (Pontis) Description	NBI Item Number	NBI Item Description
310	Elastomeric bearing (EA)	60	Sub-structure
311	Movable bearing (roller, sliding, etc) (EA)		
312	Enclosed/concealed bearing (EA)		
313	Fixed bearing (EA)		
314	Pot bearing (EA)		
315	Disk bearing (EA)		

(Hearn et al. 1997, pp5, Figure 2. Figure was Modified)

Table C.8 Bearing Elements Repair Matrix

Pontis Item	Clean – pressurized air	Clean – pressurized water	Remove bearing	Install new bearing
310	1	1	1	1
311	1	1	1	1
312	1	1	1	1
313	1	1	1	1
314	1	1	1	1
315	1	1	1	1

Table C.9 Description of Joint Elements Used by Pontis™

Pontis Item	CoRe Element (Pontis) Description
300	Strip seal expansion joint (m)
301	Pourable joint seal (m)
302	Compression joint seal (m)
303	Assembly joint seal (modular) (m)
304	Open expansion joint (m)

(Hearn et al.1997, pp5, Figure 2. Figure was Modified)

Table C.10 Joint Element Repair Matrix

Pontis Item	Clean – pressurized air	Clean – pressurized water	Remove joint	Install new joint
300	1	1	1	1
301	1	1	1	1
302	1	1	1	1
303	1	1	1	1
304	1	1	1	1

Table C.11 Description of Railing Elements Used by Pontis™

Pontis Item	CoRe Element (Pontis) Description	NBI Item Number	NBI Item Description	Material
330	Bridge railing metal coated	36 (a)	Traffic safety features	Metal coated
331	Bridge railing reinforced concrete			Concrete
332	Bridge railing timber			Timber
333	Bridge railing other			Other
334	Bridge railing metal uncoated			Metal uncoated

(Hearn et al.1997, pp5, Figure 2. Figure was Modified)

Table C.12 Railing Element Repair Matrix

Pontis Item	Clean	Remove	Install
330	1	1	1
331	1	1	1
332	1	1	1
333	1	1	1
334	1	1	1

APPENDIX D

CONSTRUCTION TASKS

Appendix D lists all construction tasks included in the flowcharts of the Construction Process Model discussed in Chapter V. Construction tasks were identified using a task identification code (task ID) and a subtask identification number (subtask ID). The same task ID – subtask ID combinations were used in the flowcharts.

Table D.1 Description of Construction Tasks and Subtasks

Task Definition	Task Identification Code	Subtask Definition	Subtask Identification Number
Concrete Removal	CR	Remove existing jacket	1
	CR	Remove existing anode	2
	CR	Sound test concrete area	3
	CR	Remove large pieces of unsound concrete	4
	CR	Remove loose particles	5
	CR	Dispose debris	6
	CR	Clean pile surface	7
	CR	Saw cut concrete to make a small excavation	8
	CR	Remove concrete to make a small excavation	9

Table D.1 (Continued)

Task Definition	Task Identification Code	Subtask Definition	Subtask Identification Number
Protective Barriers Use	PB	Place floating protective barriers	1
	PB	Remove floating protective barriers	2
Reinforcement Repair	RR	Clean reinforcement	1
	RR	Bent steel mesh	2
	RR	Place steel mesh around pile	3
	RR	Form rebar cage	4
	RR	Place rebar cage around pile	5
	RR	Weld steel mesh	6
	RR	Place additional rebar at proper location	7
	RR	Weld rebar to pile reinforcement	8
	RR	Install interior grouted post-tensioned reinforcement	9
	RR	Install interior ungrouted post-tensioned reinforcement	10
	RR	Install exterior post-tensioned reinforcement	11
Formwork Placement	FP	Move formwork to working place	1
	FP	Measure bottom formwork position	2
	FP	Install bottom formwork	3
	FP	Install lateral formwork	4
	FP	Install lateral braces	5

Table D.1 (Continued)

Task Definition	Task Identification Code	Subtask Definition	Subtask Identification Number
Soil Excavation	EX	Excavate dry soil to install bottom formwork	1
	EX	Excavate soil underwater to install bottom formwork	2
	EX	Mobilize water pump	3
	EX	Excavate wet soil to install bottom formwork	4
Jacket Placement	JP	Mobilize jackets to bridge site	1
	JP	Move jackets to working place	2
	JP	Place jackets at proper elevation	3
	JP	Apply epoxy to jackets seams	4
	JP	Snap jackets together	5
	JP	Insert jacket fasteners	6

Table D.1 (Continued)

Task Definition	Task Identification Code	Subtask Definition	Subtask Identification Number
Grout Casting	GC	Mix cement-based grout at bridge site	1
	GC	Mobilize grout truck to bridge site	2
	GC	Mobilize polymer mixing machine to bridge site	3
	GC	Mix polymer based grout	4
	GC	Mobilize grout pump to bridge site	5
	GC	Quality control: slump test	6
	GC	Quality control: strength cylinder casting	7
	GC	Pump bottom seal	8
	GC	Bottom seal curing time	9
	GC	Pump grout through injection ports	10
	GC	Move to upper injection port	11
	GC	Place grout hose at the bottom of the jacket	12
	GC	Pump grout trough a hose	13
	GC	Remove grout hose	14
	GC	Grout cast in jacket curing time	15
	GC	Clean grout waste	16

Table D.1 (Continued)

Task Definition	Task Identification Code	Subtask Definition	Subtask Identification Number
Formwork Re-moval	FR	Remove bottom formwork	1
	FR	Remove lateral braces	2
	FR	Remove lateral formwork	3
	FR	Clean formwork	4
	FR	Clean braces	5
	FR	Clean and form grout edges	6
Continuity Testing	CT	Locate reinforcement position	1
	CT	Drill holes on concrete pile to expose reinforce-ment	2
	CT	Select base reinforcement	3
	CT	Measure potential difference between base reinforcement and others	4
Concrete Patching	CP	Patch holes drilled in the concrete pile	1
	CP	Cover welds with epoxy	2
	CP	Restore small excavations on pile surface to original profile	3

Table D.1 (Continued)

Task Definition	Task Identification Code	Subtask Definition	Subtask Identification Number
Continuity Bonding	CB	Locate area of concrete to be removed	1
	CB	Connect continuity wires between existing and new reinforcement	2
	CB	Weld negative connection to transverse reinforcement	3
	CB	Connect continuity wires between pile reinforcement	4
Enclosures	EC	Remove fence	1
	EC	Replace fence	2
Reference cell installation	RC	Test reference cell	1
	RC	Locate area of concrete to be removed	2
	RC	Install reference cell	3

Table D.1 (Continued)

Task Definition	Task Identification Code	Subtask Definition	Subtask Identification Number
Pile Access	PA	Access submerged pile walking	1
	PA	Access submerged pile swimming	2
	PA	Access submerged pile using a platform and scuba diving	3
	PA	Access submerged pile using a platform and hard hat diving	4
	PA	Access submerged pile using a platform	5
	PA	Access submerged pile using a motorboat	6
	PA	Move from one pile to another walking	7
	PA	Move from one pile to another swimming	8
	PA	Move from one pile to another scuba diving	9
	PA	Move from one pile to another hard hat diving	10
	PA	Move from one pile to another with a barge	11
	PA	Move from one pile to another with a motor boat	12

APPENDIX E

CONSTRUCTION PROCESS MODEL KNOWLEDGE RULES

This appendix presents knowledge rules used by each one of the decision points of the Construction Process Model flowcharts discussed in Chapter V. The decision points are identified using the same two number combination used in the flowcharts of Chapter V. The knowledge rules that apply to the same flowchart were grouped in a single table. All decisions points in the flowchart had either a “Yes” or a “No” output option. The knowledge rules presented in the tables stated the condition that should be true for the model to select the output option listed in the table. In most cases, the knowledge rule decision was triggered by an input parameter. Input parameters were described before discussing the decision rules. Additional input parameters listed in the tables were required only if the knowledge rule discussed was executed.

Input and output values corresponding to the example used in Chapter V are shown highlighted on the tables. The example refers to prestressed concrete pile number 6 located on span 6 of the Howard Frankland Bridge. The FDOT Bridge Number was 150107. The bridge carried interstate I-275 over the Old Tampa Bay. The Pontis™ element used to classify the pile was 226. The author gathered the input parameters from FDOT design plans. The damage data were gathered from FDOT detail inspection reports. Damage data were stored in the Damage Assessment Model as described in Chapter IV. For the example pile, the repair method selected was an integral CP jacket with a sacrificial zinc anode. The reinforcement repair method selected was to add a cage of mild steel reinforcing bars. Cement grout was specified for the repair of the example pile.

Construction activities marked with an asterisk in the flowcharts in Chapter V needed to be performed only once for a group of piles. The author did not implement a tool to group elements to count elements in a group or to differentiate between elements in different groups. Furthermore, the author did not implement a tool to assign group related construction tasks only once to a group. If it was required to define a group of elements for the knowledge rule that selected group related construction tasks, such a group was described on the table under the column discussing additional input. To illustrate the methodology, the author assumed that it would be possible to implement such a grouping tool in the future. Furthermore, the author assumed that the model could recognize which was the first and last element in the group being repaired. Such data were marked with an asterisk in the tables. The first and last element of a group was used to trigger the execution of knowledge rules. Development of the grouping tool described is recommended for future research.

Pile Access Module Flowchart

The pile access module flowchart required the following input parameters:

- Type of access (user input). User options: fenced or free.
- Type of environment around the pile (user input). User options: waterway, roadway or other.
- Damage location (Damage Assessment Model or user input).

Table E.1 Knowledge Rules for the Pile Access Module Flowchart

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
2-1 Is the working area surrounded by a fence?	If type of access selected by the user was:	Fence	Yes	The user should be asked to group elements enclosed by a fence. Assumed such a group was called a "fence group".
		Free	No	Not required
2-2 Is the working area surrounded by water?	If type of environment selected by the user was:	Waterway	Yes	1) The user should be asked to group elements that will be repaired simultaneously. Assume such a group was called a "water access group". 2) Pile accessibility matrix input: A) Water depth. B) Damage location.
		Different than waterway	No	Not required
2-3 Do floating protective barriers need to be placed?	If element was the first element in the "water access group" or if no "water access" group was defined.	* "Water access group" data	Yes	The author assumed these output values for the example pile.
	All other elements in the "water access" group."	* "Water access group" data	No	Not required

Table E.1 (Continued)

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
2-4 Is the working area surrounded by vehicular traffic?	If type of environment selected by the user was:	Roadway	Yes	The user should be asked to group elements that require having traffic control devices in place while being repaired. Assume such a group was called a "traffic control" group.
		Different than roadway	No	Not required
	Note: decision point 2-4 was not required for the example pile. See the pile access module flowchart, Figure 5.6.			
2-5 Are appropriate traffic control devices in place?	If element was the first element in the "traffic control group"	* "Traffic control group" data	Yes	Not required
	All other elements in the "traffic control group"	* "Traffic control group" data	No	Not required
	Note: decision point 2-5 was not required for the example pile. See the pile access module flowchart, Figure 5.6.			
2-6 Does fence need to be replaced?	If type of access selected by the user was:	Free	No	Not required
		Fence	See knowledge rules A and B below	Not required
	A) If element was the last element in the "fence group"	* "Fence group" data	Yes	Not required
	B) All other elements in the "fence group"	* "Fence group" data	No	Not required

Table E.1 (Continued)

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
2-7 Do floating protective barriers need to be removed?	If type of environment selected by the user was:	Different than waterway	No	Not required
		Waterway	See knowledge rules C and D below	Not required
	C) If element was the last element in the "water access group"	* "Water access group" data	Yes	Not required
	D) All other elements in the "water access group"	* "Water access group" data	No	Not required
2-8 Do traffic control devices need to be removed?	If type of environment selected by the user was:	Other than roadway	No	Not required
		Roadway	See knowledge rules E and F below	Not required
	E) If element was the last element in "traffic control group"	* "Traffic control group" data	Yes	Not required
	F) All other elements in the "traffic control group"	* "Traffic control group" data	No	Not required

Concrete Removal Module Flowchart

The concrete removal module flowchart required the following input parameters:

- Type of protection systems already installed on the pile (user input). User options: jacket, anode, none.
- Type of repair method (user input). This parameter was already selected by the user from a list of options generated from the repair matrices discussed earlier. For a concrete pile such options were:

Option 1: Integral CP jacket with sacrificial anode mesh.

Option 2: Integral CP jacket with impressed current anode mesh.

Option 3: All polymer encapsulation.

Option 4: Hybrid fiber epoxy composites.

- Dimensions of unsound concrete area (Damage Assessment Model).

Table E.2 Knowledge Rules for the Concrete Removal Module Flowchart

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
3-1 Is there an existing jacket on the pile?	If type of protection system already installed on the pile is:	Jacket	Yes	Not required
		Different than jacket	No	Not required
3-2 Does the repair method include a CP system?	If repair method selected was:	Option 1	Yes	Not required
		Option 2	Yes	Not required
		Option 3	No	Not required
		Option 4	No	Not required
3-3 Is there an existing anode on the pile?	If type of protection system was:	Jacket	Yes	Not required
		Anode	No	Not required
		None	No	Not required
3-4 Is there unsound concrete on the pile?	Spall length > 0 or Spall width >0 or Spall depth >0	Spall dimensions	Yes	If there was unsound concrete on the pile the spall dimensions were stored in the Damage Assessment Model.
	Spall length = 0 or Spall width = 0 or Spall depth = 0	Spall dimensions	No	Not required

Table E.2 (Continued)

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
3-5 Need to dispose of debris?	If element was the last element in the "cleaning group"	* "Clean-ing group" data	No	The user should be asked to group elements that will be cleaned at the same time after finishing the construc-tion activities. Assume such group was called the "cleaning group". If ele-ments are surrounded by water, then the "cleaning group" could be the same as the "water access group".
	All other elements in the "cleaning group"	* "Clean-ing group" data	Yes	

Reinforcement Repair Module Flowchart

The parameters that were required by the reinforcement repair module flowchart include:

- Corrosion data (damage assessment or user input). The model needed to know whether there was corrosion or not. If there was corrosion, then the model needed to know the amount of reinforcement cross-section loss.
- Type of reinforcement in the pile (user input). User options: prestressed steel strands, mild steel reinforcing bars (rebars), default.
- Type of additional/replacement reinforcement (user input). User options were those shown in the repair matrices and consisted of adding or replacing:

Steel rebar cage.

Lap weld rebar.

Wire mesh.

External post-tensioned steel strands.

Internal ungrouted post-tensioned steel strands.

Internal grouted post-tensioned steel strands.

External post-tensioned FRP.

Internal ungrouted post-tensioned FRP.

Internal grouted post-tensioned steel FRP.

External post-tensioned steel rebar.

Internal ungrouted post-tensioned steel rebar.

Internal grouted post-tensioned steel rebar.

None.

Default.

Table E.3 Knowledge Rules for the Reinforcement Repair Module Flowchart

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
4-1 Is there rein-forcement corrosion?	If Reinforcement cross section loss >0 or Length of reinforcing missing >0	Reinforcement corrosion data	Yes	Not required
	If Reinforcement cross section loss = 0 or Length of reinforcing missing = 0	Reinforcement corrosion data	No	Not required

Table E.3 (Continued)

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
4-2 Is there considerable cross section loss on reinforcement (25% or more)?	If Reinforcement cross section loss =>25%	Reinforcement corrosion data	Yes	Not required
	If Reinforcement cross section loss < 25%	Reinforcement corrosion data	No	Not required
4-3 Provide additional reinforcement?	If type of reinforcement repair option selected by the user was:	None	No	Not required
		Different than none	Yes	Not required
4-4 Provide additional steel mesh?	If type of reinforcement repair option selected by the user was:	Wire mesh	Yes	Not required
		Different than wire mesh	No	Not required
4-5 Provide additional rebars (mild steel reinforcing rebars)?	If type of reinforcement repair option selected by the user was:	Steel rebar or Lap weld rebar or Rebar cage	Yes	Not required
		Different than steel rebar, lap weld rebar and rebar cage	No	Not required
4-6 Is pile reinforcement prestressed?	If type of reinforcement in the pile was:	Prestressed steel strands.	Yes	Not required
		Mild steel reinforcing bars.	No	Not required

Table E.3 (Continued)

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
4-7 Use a lap weld rebar?	If type of reinforcement repair option selected by the user was:	Lap weld rebar.	Yes	Not required
		Different than lap weld rebar.	No	Not required
	Note: decision point 4-7 was not executed for the example pile. See the reinforcement repair module flowchart, Figure 5.9.			
4-8 Provide exterior prestressing?	If type of reinforcement repair option selected by the user was:	External post-tensioned (EPT) FRP or EPT steel strands or EPT steel rebars.	Yes	Not required
		Different than EPT FRP or EPT PT steel strands or EPT PT steel rebars.	No	Not required
	Note: decision point 4-8 was not executed for the example pile. See the reinforcement repair module flowchart, Figure 5.9.			
4-9 Grouted reinforcement?	If type of reinforcement repair option selected by the user was:	Internal grouted post-tensioned (IGPT) FRP or IGPT steel strands or IGPT steel rebars	Yes	Not required
		Internal ungrouted post-tensioned (IUPT) FRP or IUPT steel strands or IUPT steel rebars	No	Not required
	Note: decision point 4-9 was not executed for the example pile. See the reinforcement repair module flowchart, Figure 5.9.			

Table E.3 (Continued)

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
4-10 Does cathodic protection need to be included?	If type of repair method selected on the concrete repair module flowchart input parameters was:	Option 1 or Option 2	Yes	Not required
		Different than Option 1 or Option 2	No	Not required

Continuity Bonding Module Flowchart

The parameters required by the continuity bonding module flowchart include:

- Type of reinforcement in the pile (user input). User options: prestressed steel strands, mild steel reinforcing bars, default.
- Probability of having discontinuous strands on any column face (user input). The user could either provide a probability or use the default values stored in the probability matrix show in Tables E.4 and E.5.

The parameters required by the continuity bonding module flowchart were empirical probabilities. Default values were proposed based on data analyzed by the author and were discussed in Chapter VII. Such default values have been organized in two tables according to the type of reinforcement on the pile. Table E.4 refers to piles with prestressed steel strands. Table E.5 refers to piles with mild reinforcement steel bars.

Table E.4 Table of Empirical Probabilities for Piles with Prestressed Steel Strands

Decision Point	Probability that the output value is "Yes"	Probability that the output value is "No"
5-1 Are there discontinuous strands on any column face?	.29	.71
5-2 Are there three or more discontinuous strands on the column face under consideration?	.15	.85
5-3 Is there an existing excavation for the negative connection?	.29	.71

Table E.5 Table of Empirical Probabilities for Piles with Mild Reinforcing Steel Bars

Decision Point	Probability that the output value is "Yes"	Probability that the output value is "No"
5-1 Are there any discontinuous strands on any column face	0.0	1.0
5-2 Are there three or more discontinuous strands on the column face under consideration	0.0	1.0
5-3 Is there an existing excavation for the negative connection	0.0	1.0

Formwork Placement Module Flowchart

The parameters required by the formwork placement module flowchart were:

- Type of formwork used (user input). User options: bottom formwork only, lateral formwork only, bottom and lateral formwork, none.
- Existing soil elevation (user input).
- Bottom of jacket elevation (user input).

If the pile was surrounded by water, then the user should input the water elevation (MLW).

Table E.6 Knowledge Rules for the Formwork Placement Module Flowchart

Decision Point	Knowledge Rule	Parameter	Output	Additional input parameters
6-1 Does the jacket require bottom formwork?	If the type of formwork selected by the user was:	Bottom formwork only or bottom and lateral formwork	Yes	Not required
		Lateral formwork only or none	No	Not required
6-2 Is excavation required to install bottom formwork?	If the existing soil elevation> jacket bottom elevation	Existing soil elevation and bottom jacket elevation	Yes	Not required
	If the existing soil elevation< jacket bottom elevation	Existing soil elevation and bottom jacket elevation	No	Not required
6-3 Is the pile submerged in water?	(Refer to pile access module), if type of environment around pile was:	Waterway	Yes	Water elevation (MLW)
		Different than waterway	No	Not required
	Note: decision point 6-3 was not executed for the example pile. See the formwork placement module flowchart, Figure 5.13.			
6-4 Is the water depth 1 foot or more?	If water elevation (MLW) – existing soil elevation > 1	Water elevation and existing soil elevation	Yes	Not required
	If water elevation (MLW) – existing soil elevation < 1	Water elevation and existing soil elevation	No	Not required
	Note: decision point 6-4 was not executed for the example pile. See the formwork placement module flowchart, Figure 5.13.			
6-5 Does the jacket require lateral formwork?	If the type of formwork selected by the user was:	Lateral formwork only or bottom and lateral formwork	Yes	Not required
		Bottom formwork only or none	No	Not required

Jacket Placement Module Flowchart

The type of repair was the only input parameter required by the jacket placement module. The user already selected the type of repair because it was required for the module selection flowchart.

Table E.7 Knowledge Rules for the Jacket Placement Module Flowchart

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
7-1 Will the jacket stay in place?	If the type of repair selected by the user was:	Integral CP jacket with sacrificial anode mesh Integral CP jacket with impressed current anode mesh All polymer encapsulation	Yes	Not required
		Hybrid fiber epoxy composites	No	Not required

Grout Casting Module Flowchart

The input parameter required by the grout casting modules was:

- Type of repair method (user input). The user was required to enter this input for the module selection flowchart.

In addition, the user should define a group of elements for which the grout was cast simultaneously. The author assumed that such a group was called a “grout casting group”.

Table E.8 Knowledge Rules for the Grout Casting Module Flowchart

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
8-1 Is the equip-ment required to cast the grout already at the bridge site?	If the pile was the first element in the “grout casting group”	* “Grout casting group” data	No	Not required
	If the pile was not the first element in the “grout casting group	* “Grout casting group” data	Yes	Not required
8-2 Does the jacket require a polymer bottom seal?	If type of repair method selected as an input parameter for the concrete repair module flowchart was:	All polymer encapsulation	Yes	Not required
		Different than all polymer encapsulation	No	Not required
8-3 Does the jacket have injection ports?	If type of repair method selected as an input parameter for the concrete repair module flowchart was:	All polymer encapsulation	Yes	Not required
		Different than all polymer encapsulation	No	Not required
8-4 Does the grout casting equip-ment need to stay at the bridge site?	If the pile was the first element in the “grout casting group”	* “Grout casting group” data	Yes	Not required
	If the pile was not the first element in the “grout casting group	* “Grout casting group” data	No	Not required

Grout Mobilization Module Flowchart

The input parameters required by the grout mobilization flowchart were:

- Type of grout (user input). User options: cement, polymer.
- Grout mixing location (user input). User options: On site, factory.

Table E.9 Knowledge Rules for the Grout Mobilization Module Flowchart

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
9-1 Does the construction task require cement based grout?	If type of grout selected by the user was:	Cement	Yes	Not required
		Polymer	No	Not required
9-2 Is grout mixed at bridge site?	If grout mixing location selected by the user was:	On site	Yes	Not required
		Factory	No	Not required
9-3 Does the construction task require polymer grout?	If type of grout selected by the user was:	Polymer	Yes	Not required
		Cement	No	Not required
	Note: decision point 9-3 was not executed for the example pile. See the grout mobilization module flowchart, Figure 5.16.			

Formwork Removal Module Flowchart

The only parameter that was required by the system to make decisions was the type of formwork, which was already input by the user when required to select the input parameters for the formwork placement module flowchart.

Table E.10 Knowledge Rules for the Formwork Removal Module Flowchart

Decision Point	Knowledge Rule	Parameter	Output	Additional Input Parameters
10-1 Does the system require bottom form-work?	If type of formwork selected by the user was:	Bottom formwork only or bottom and lateral form-work	Yes	Not required
		Lateral formwork only or none	No	Not required
10-2 Does the system require lateral form-work?	If type of formwork selected by the user was:	Lateral formwork only or bottom and lateral form-work	Yes	Not required
		Bottom formwork only or none	No	Not required

APPENDIX F

CONSTRUCTION PROCESS MODEL QUERIES

Appendix F presents the SQL code query that was developed by the author to retrieve data stored in the Construction Process Model.

Report Wizard

The purpose of the report shown in Figures 5.24 and 5.25, Example 5.5.1, was to list all construction tasks required to repair a specific element within a given estimate. The report was generated using the Microsoft® Access Report Wizard shown in Figure F.1. The report was based on data retrieved from a sample database created in Microsoft® Access (2000) using Query F.1 listed below.

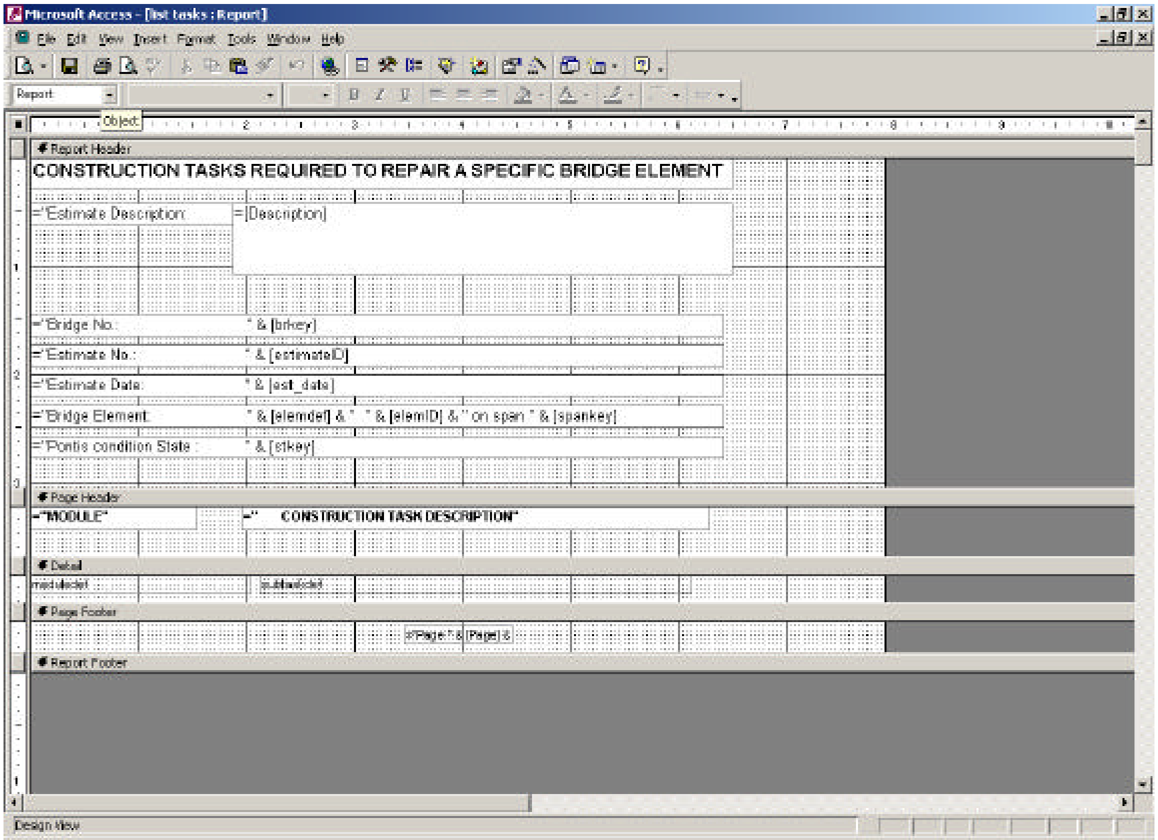

Figure F.1. Microsoft® Access Report Wizard Used to Create the Report Shown in Figures 5.24 and 5.25

Query F.1

```
SELECT   estimate_element.[est-elemID], estimate_element.estimateID,
         estimate_element.brkey, estimate_element.elemkey,
         estimate_element.spankey, estimate_element.elemID, estimate.est_date,
         estimate.description, elementdef.elemdef, element.stkey,
         estimate_task.[est-taskID], module.moduledef, estimate_task.taskID,
         task.taskdef, estimate_task.subtaskID, subtask.subtaskdef

FROM task INNER JOIN
    (subtask INNER JOIN
        ([module] INNER JOIN
            (estimate INNER JOIN
                (((element INNER JOIN elementdef
                ON element.elemkey = elementdef.elemkey
                INNER JOIN estimate_element
                ON (element.elemID = estimate_element.elemID) AND
                    (element.spankey = estimate_element.spankey) AND
                    (element.elemkey = estimate_element.elemkey) AND
                    (element.brkey = estimate_element.brkey) AND (ele-
                    mentdef.elemkey = estimate_element.elemkey))
                INNER JOIN estimate_task
                ON estimate_element.[est-elemID] =
                    estimate_task.[est-elemID])
            ON estimate.estimateID = estimate_element.estimateID)
        ON module.moduleID = estimate_task.moduleID)
    ON (subtask.subtaskID = estimate_task.subtaskID) AND
        (subtask.taskID = estimate_task.taskID))
ON (task.taskID = subtask.taskID) AND  (task.taskID = estimate_task.taskID)

WHERE (((estimate_element.[est-elemID])=
         [enter estimate element identification number]))

ORDER BY estimate_task.[est-taskID];
```

Sample Database Tables

The query described in Appendix F retrieved data from a sample database created by the author. The results of Query F.1 were used to generate the reports shown in Figures 5.24 and 5.25 and are presented in Tables F.1 through F.3. Table F.1 lists the construction tasks selected within estimate number one for the example pile (prestressed concrete pile 6 on span 6 bridge 150107), which includes all construction tasks highlighted in the construction flowcharts in Chapter V. The columns highlighted in Table F.1 were included in the report shown in Figures 5.24 and 5.25.

Data shown in Tables F.2 and F.3 were common for each set of data shown in Table F.1, so the author presented the data in separate tables for clarity even though Query F.1 produced a single table. Table F.2 provides the estimate identification number (estimateID), the estimate date (est_date), and a description of the estimate (description). Table F.3 provide the element identification number for a given estimate (est-elemID), the bridge identification number (brkey), the Pontis™ element type (elemkey), a short description of the Pontis™ element (elemdef), the bridge span where the element is located (spankey) and the element identification number within the given bridge (elemID).

Data stored in the sample database are shown in Tables F.4 through F.11. Such tables were developed using the entities described in Chapter V and Chapter IV, and were labeled with the same name used to label the entities to which they referred. The tables included the data for the example pile (pile 6 span 6 of bridge 150107, shown highlighted) as well as additional data for other elements, bridges and estimates. Additional data were included to insure that the query retrieved only the data of interest.

Table F.1 Results of Query F.1 for the Example Pile

est-taskID	*moduledef*	*taskID*	*sub-taskID*	*subtaskdef*
1	PILE ACCESS	PB	1	Place floating protective barriers
2	PILE ACCESS	PA	5	Access submerged pile using a platform
3	CONCRETE REMOVAL	CR	3	Sound test concrete area
4	CONCRETE REMOVAL	CR	4	Remove large pieces of unsound concrete
5	CONCRETE REMOVAL	CR	5	Remove loose particles and remaining unsound concrete
6	REINFORCEMENT REPAIR	RR	1	Clean reinforcement
7	REINFORCEMENT REPAIR	RR	4	Form rebar cage
8	REINFORCEMENT REPAIR	RR	5	Place rebar cage around pile
9	REINFORCEMENT REPAIR	CB	2	Connect continuity wires between existing and new reinforcement
10	REINFORCEMENT REPAIR	CR	7	Clean pile surface
11	CONTINUITY TESTING	CT	1	Locate reinforcement position
12	CONTINUITY TESTING	CT	2	Drill holes on concrete pile to expose reinforcement
13	CONTINUITY TESTING	CT	3	Select base reinforcement
14	CONTINUITY TESTING	CT	4	Measure potential difference between base reinforcement and others
15	CONTINUITY TESTING	CP	1	Patch holes drilled in the concrete pile
16	CONTINUITY BONDING	CB	1	Locate area of concrete to be removed
17	CONTINUITY BONDING	CR	8	Saw cut concrete to make a small excavation
18	CONTINUITY BONDING	CR	9	Remove concrete to make a small excavation
19	CONTINUITY BONDING	CB	4	Connect continuity wires between existing pile reinforcement
20	CONTINUITY BONDING	CB	3	Weld negative connection to transverse reinforcement
21	CONTINUITY BONDING	CP	2	Cover welds with epoxy

Table F.1 (Continued)

est-taskID	*moduledef*	*taskID*	*sub-taskID*	*subtaskdef*
22	CONTINUITY BONDING	CP	3	Restore small excavations on pile surface to original profile
23	REFERENCE CELL INSTALLATION	RC	1	Test reference cell
24	REFERENCE CELL INSTALLATION	RC	2	Locate area of concrete to be removed
25	REFERENCE CELL INSTALLATION	CR	9	Remove concrete to make a small excavation
26	REFERENCE CELL INSTALLATION	RC	3	Install reference cell
27	REFERENCE CELL INSTALLATION	CP	3	Restore small excavations on pile surface to original profile
28	FORMWORK PLACEMENT	FP	1	Move formwork to working place
29	FORMWORK PLACEMENT	FP	2	Measure bottom formwork position
30	FORMWORK PLACEMENT	FP	3	Install bottom formwork
31	JACKET PLACEMENT	JP	1	Mobilize jackets to bridge site
32	JACKET PLACEMENT	JP	2	Move jacket to working place
33	JACKET PLACEMENT	JP	3	Place jacket at proper elevation
34	JACKET PLACEMENT	JP	4	Apply epoxy to jacket seams
35	JACKET PLACEMENT	JP	5	Snap jackets together
36	JACKET PLACEMENT	JP	6	Insert jacket fasteners
37	FORMWORK PLACEMENT	FP	4	Install lateral formwork
38	FORMWORK PLACEMENT	FP	5	Install lateral braces
39	GROUT MOBILIZATION	GC	2	Mobilize grout truck to bridge site
40	GROUT MOBILIZATION	GC	5	Mobilize grout pump to bridge site
41	GROUT MOBILIZATION	GC	6	Quality control: slump test
42	GROUT MOBILIZATION	GC	7	Quality control: strength cylinder casting
43	GROUT MOBILIZATION	GC	12	Place grout hose at the bottom of the jacket

Table F.1 (Continued)

est-taskID	*moduledef*	*taskID*	*sub-taskID*	*subtaskdef*
44	GROUT CASTING	GC	13	Pump grout trough a hose
45	GROUT CASTING	GC	14	Remove grout hose
46	GROUT CASTING	GC	15	Grout cast in jacket curing time
47	GROUT CASTING	GC	16	Clean grout waste
48	FORMWORK REMOVAL	FR	1	Remove bottom formwork
49	FORMWORK REMOVAL	FR	4	Clean formwork
50	FORMWORK REMOVAL	FR	2	Remove lateral braces
51	FORMWORK REMOVAL	FR	5	Clean braces
52	FORMWORK REMOVAL	FR	3	Remove lateral formwork
53	FORMWORK REMOVAL	FR	4	Clean formwork
54	FORMWORK REMOVAL	FR	6	Clean and form grout edges

Table F.2 Results of Query F.1 for the Example Pile (Subset 2)

est-elemID	*estimateID*	*est_date*	*description*
1	1	10-Jan-04	Install integral cathodic protection jackets with sacrificial anode mesh on bridge piles

Table F.3 Results of Query F.1 for the Example Pile (Subset 3)

est-elemID	*brkey*	*elemkey*	*elemendef*	*spankey*	*elemID*	*stkey*
1	150107	226	Prestressed concrete pile	6	6	4

Table F.4 “Task” Table

taskID	*taskdef*
CB	Continuity bonding
CP	Concrete Repair
CR	Concrete Removal
CT	Continuity Testing
EC	Enclosure
EX	Soil excavation
FP	Formwork Placement
FR	Formwork Removal
GC	Grout Casting
JP	Jacket Placement
PA	Pile Access
PB	Protective Barriers Use
RC	Reference Cell Installation
RR	Reinforcement Repair

Table F.5 “Subtask” Table

taskID	*subtask ID*	*taskdef*
CB	1	Locate area of concrete to be removed
CB	2	Connect continuity wires between existing and new reinforcement
CB	3	Weld negative connection to transverse reinforcement
CB	4	Connect continuity wires between pile reinforcement
CP	1	Patch holes drilled in the concrete pile
CP	2	Cover welds with epoxy

Table F.5 (Continued)

taskID	*subtask ID*	*taskdef*
CP	3	Restore small excavations on pile surface to original profile
CR	1	Remove existing jacket
CR	2	Remove existing anode
CR	3	Sound test concrete area
CR	4	Remove large pieces of unsound concrete
CR	5	Remove loose particles and remaining unsound concrete
CR	6	Dispose of debris
CR	7	Clean pile surface
CR	8	Saw cut concrete to make a small excavation
CR	9	Remove concrete to make a small excavation
CT	1	Locate reinforcement position
CT	2	Drill holes on concrete pile to expose reinforcement
CT	3	Select base reinforcement
CT	4	Measure potential difference between base reinforcement and others
EC	1	Remove fence
EC	2	Replace fence
EX	1	Excavate dry soil to install bottom formwork
EX	2	Excavate soil underwater to install bottom formwork
EX	3	Mobilize water pump
EX	4	Excavate wet soil to install bottom formwork
FP	1	Move formwork to working place
FP	2	Measure bottom formwork position
FP	3	Install bottom formwork

Table F.5 (Continued)

taskID	*subtask ID*	*taskdef*
FP	4	Install lateral formwork
FP	5	Install lateral braces
FR	1	Remove bottom formwork
FR	2	Remove lateral braces
FR	3	Remove lateral formwork
FR	4	Clean formwork
FR	5	Clean braces
FR	6	Clean and form grout edges
GC	1	Mix cement-based grout at bridge site
GC	2	Mobilize grout truck to bridge site
GC	3	Mobilize polymer mixing machine to bridge site
GC	4	Mix polymer based grout
GC	5	Mobilize grout pump to bridge site
GC	6	Quality control: slump test
GC	7	Quality control: strength cylinder casting
GC	8	Pump bottom seal
GC	9	Bottom seal curing time
GC	10	Pump grout through injection ports
GC	11	Move to upper injection port
GC	12	Place grout hose at the bottom of the jacket
GC	13	Pump grout through a hose
GC	14	Remove grout hose
GC	15	Grout cast in jacket curing time

Table F.5 (Continued)

taskID	*subtask ID*	*taskdef*
GC	16	Clean grout waste
JP	1	Mobilize jackets to bridge site
JP	2	Move jacket to working place
JP	3	Place jacket at proper elevation
JP	4	Apply epoxy to jacket seams
JP	5	Snap jackets together
JP	6	Insert jacket fasteners
PA	1	Access submerged pile walking
PA	2	Access submerged pile swimming
PA	3	Access submerged pile using a platform and scuba diving
PA	4	Access submerged pile using a platform and hard hat diving
PA	5	Access submerged pile using a platform
PA	6	Access submerged pile using a motorboat
PA	7	Move from one pile to another walking
PA	8	Move from one pile to another swimming
PA	9	Move from one pile to another scuba diving
PA	10	Move from one pile to another hard hat diving
PA	11	Move from one pile to another with a barge
PA	12	Move from one pile to another with a motor boat
PB	1	Place floating protective barriers
PB	2	Remove floating protective barriers
RC	1	Test reference cell
RC	2	Locate area of concrete to be removed

Table F.5 (Continued)

taskID	*subtask ID*	*taskdef*
RC	3	Install reference cell
RR	1	Clean reinforcement
RR	2	Bent steel mesh
RR	3	Place steel mesh around pile
RR	4	Form rebar cage
RR	5	Place rebar cage around pile
RR	6	Weld steel mesh
RR	7	Place additional rebar at proper location
RR	8	Weld rebar to pile reinforcement
RR	9	Install interior grouted post-tensioned reinforcement
RR	10	Install interior ungrouted post-tensioned reinforcement
RR	11	Install exterior post-tensioned reinforcement

Table F.6 “Estimate” Table

estimateID	*est_date*	*description*
1	1/10/2004	Install integral cathodic protection jackets with sacrificial anode mesh on bridge piles
2	1/12/2004	Provide exterior post-tensioned reinforcement to pile
3	1/15/2004	Provide additional steel mesh to pile
4	1/16/2004	Remove existing jacket

Table F.7 “Estimate_element” Table

<u>est-elemID</u>	*estimateID*	***brkey***	***elemkey***	***spankey***	*elemID*
1	1	150107	226	6	6
2	1	150107	226	12	8
3	1	150107	226	13	3
4	2	150107	226	6	6
5	3	150107	226	6	6
6	4	720076	227	46	1

Table F.8 “Module” Table

<u>moduleID</u>	*moduledef*
1	MODULE SELECTION
2	PILE ACCESS
3	CONCRETE REMOVAL
4	REINFORCEMENT REPAIR
5	CONTINUITY BONDING
6	FORMWORK PLACEMENT
7	JACKET PLACEMENT
8	GROUT CASTING
9	GROUT MOBILIZATION
10	FORMWORK REMOVAL
11	CONTINUITY TESTING
12	REFERENCE CELL INSTALLATION

Table F.9 “Estimate_task” Table

est-taskID	*est-elemID*	*moduleID*	*taskID*	*subtaskID*
1	1	2	PB	1
2	1	2	PA	5
3	1	3	CR	3
4	1	3	CR	4
5	1	3	CR	5
6	1	4	RR	1
7	1	4	RR	4
8	1	4	RR	5
9	1	4	CB	2
10	1	4	CR	7
11	1	11	CT	1
12	1	11	CT	2
13	1	11	CT	3
14	1	11	CT	4
15	1	11	CP	1
16	1	5	CB	1
17	1	5	CR	8
18	1	5	CR	9
19	1	5	CB	4
20	1	5	CB	3
21	1	5	CP	2
22	1	5	CP	3
23	1	12	RC	1
24	1	12	RC	2

Table F.9 (Continued)

est-taskID	*est-elemID*	*moduleID*	*taskID*	*subtaskID*
25	1	12	CR	9
26	1	12	RC	3
27	1	12	CP	3
28	1	6	FP	1
29	1	6	FP	2
30	1	6	FP	3
31	1	7	JP	1
32	1	7	JP	2
33	1	7	JP	3
34	1	7	JP	4
35	1	7	JP	5
36	1	7	JP	6
37	1	6	FP	4
38	1	6	FP	5
39	1	9	GC	2
40	1	9	GC	5
41	1	9	GC	6
42	1	9	GC	7
43	1	9	GC	12
44	1	8	GC	13
45	1	8	GC	14
46	1	8	GC	15
47	1	8	GC	16

Table F.9 (Continued)

est-taskID	*est-elemID*	*moduleID*	*taskID*	*subtaskID*
48	1	10	FR	1
49	1	10	FR	4
50	1	10	FR	2
51	1	10	FR	5
52	1	10	FR	3
53	1	10	FR	4
54	1	10	FR	6
100	2	3	CR	3
101	2	3	CR	4
102	2	3	CR	5
200	3	2	CR	3
201	3	2	CR	4
202	3	2	CR	5
300	4	4	RR	1
301	4	4	RR	11
302	4	4	CB	2
303	4	4	CR	7
400	5	4	RR	1
401	5	4	RR	2
402	5	4	RR	3
403	5	4	RR	6
404	5	4	CB	2
405	5	4	CR	7

Table F.9 (Continued)

est-taskID	*est-elemID*	*moduleID*	*taskID*	*subtaskID*
500	6	3	CR	1
501	6	3	CR	3
502	6	3	CR	4
503	6	3	CR	5

Table F.10 "Element Table"

brkey	***elemkey***	***spankey***	*elemID*	***skey***
150107	226	6	6	4
150107	226	12	8	2
150107	226	13	3	4
150107	226	52	1	2
720076	227	46	1	2

Table F.11 "Elementdef" Table

elemkey	*elemdef*
204	Prestressed concrete pile extension
205	Reinforced concrete pile extension
226	Prestressed concrete pile
227	Reinforced concrete pile

APPENDIX G

PARAMETRIC QUANTITY MODEL QUERIES

Appendix G presents the SQL code query that was developed by the author to retrieve data stored in the Parametric Quantity Model.

Report Wizard G.1

The purpose of the report shown in Figure 6.3 and Example 6.3.1 was to list the quantity items required to repair a specific element within a given estimate. The report was generated using the Microsoft® Access (2000) Report Wizard shown in Figure G.1. The report was based on data retrieved from a sample database created in Microsoft® Access (2000) using Query G.1 listed below. The data stored in the database were limited to the quantity items related to the Jacket Placement Module and the Continuity Bonding Module.

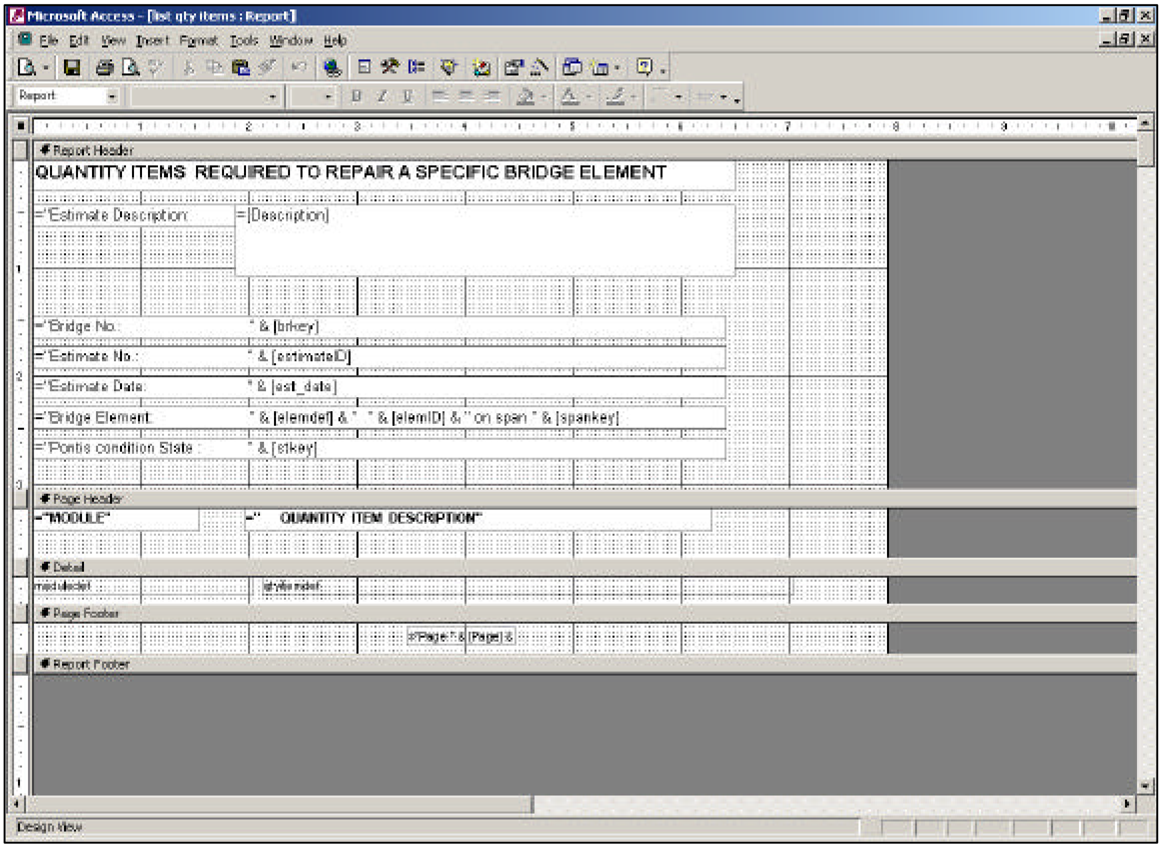

Figure G.1. Microsoft® Access Report Wizard Used to Create the Report Shown in Figure 6.3

Query G.1

```
SELECT    estimate_task.[est-elemID], estimate_task.moduleID, estimate.estimateID,
          estimate_task.taskID, qty_item.qtyitemID, qty_item.qtyitemdef,
          module.moduledef, estimate.description, estimate.est_date,
          estimate_element.brkey, estimate_element.elemkey,
          estimate_element.spankey, estimate_element.elemID, element.stkey,
          elementdef.elemdef
FROM
        (subtask INNER JOIN
                ([module] INNER JOIN
                        (estimate INNER JOIN
                                (((elementdef INNER JOIN element
                                ON elementdef.elemkey = element.elemkey)
                                INNER JOIN estimate_element
                                ON (element.elemID = estimate_element.elemID) AND
                                    (element.spankey = estimate_element.spankey) AND
                                    (element.elemkey = estimate_element.elemkey) AND
                                    (element.brkey = estimate_element.brkey) AND
                                    (elementdef.elemkey = estimate_element.elemkey))
                                INNER JOIN estimate_task
                                ON estimate_element.[est-elemID] =
                                    estimate_task.[est-elemID])
                        ON estimate.estimateID = estimate_element.estimateID)
                ON module.moduleID = estimate_task.moduleID)
        ON (subtask.subtaskID = estimate_task.subtaskID) AND
            (subtask.taskID = estimate_task.taskID))
        INNER JOIN (qty_item
                INNER JOIN task
                ON qty_item.taskID = task.taskID)
        ON (task.taskID = subtask.taskID) AND
            (task.taskID = estimate_task.taskID) AND
            (subtask.subtaskID = qty_item.subtaskID) AND
            (subtask.taskID = qty_item.taskID)
WHERE (((estimate_task.[est-elemID])=[Enter Element-estimate ID]) AND
        ((estimate_task.moduleID)=5 Or (estimate_task.moduleID)=7));
```

APPENDIX H

SAMPLE EQUATIONS AND KNOWLEDGE RULES USED BY THE PARAMETRIC QUANTITY MODEL

To illustrate the Parametric Quantity Model, two examples were developed. Example H.1 referred to quantity equations related to the Jacket Placement Module, and Example H.2, to the Continuity Bonding Module. Default values for the parameters used in the equations were defined either by expert knowledge or by analysis of design plans and specifications of FDOT repair projects. The default values were the values that occurred most often (mode). Minimum and maximum values were also provided.

Required parameters for Example H.1 and H.2 are listed in Table H.1. In Table H.1, there are two parameters that refer to the number of jackets ("$\text{jacket}_{\text{number}}$" and "$\text{jacket}_{\text{tot\_number}}$"). The distinction was made because within the same project the user should have the option to estimate quantities for a group of jackets ("$\text{jacket}_{\text{number}}$") since jacket dimensions may change within the same project, repair on several bridges may be grouped in a single project or the user may just want to look at a single pile, as in the example discussed later.

On the other hand, some fixed costs should be evenly divided among the total number of jackets regardless of how the user chose to group the jackets. Similarly, quantities related to the Continuity Bonding Module, were calculated using empirical probabilities and were independent of the number of jackets grouped by the user. In such cases quantities were first calculated based on the total number of jackets in the project

(“$jacket_{tot\_number}$ ”), and then a fraction of the total quantity was assigned to each jacket under consideration ($1/jacket_{tot\_number}$).

The example considered in the previous chapters referred to pile 6 on span 6 of the Howard Frankland Bridge (Bridge No. 150107). Example H.1 corresponded to a single pile. The repair of the Howard Frankland Bridge involved 231 piles. The project included repairs on eight more piles on the Gandy Bridge. Thus the total number of piles was 239.

The quantities calculated in Example H.2 were calculated based on the total number of piles repaired (239 piles); then, only a fraction of the quantities calculated (1/239) was assigned to the pile considered.

Table H.1 Required Parameters Used by the Model to Calculate Jacket Quantities

Parameter	Parameter Description	Example Pile
$Jacket_{number}$	Number of jackets under consideration	1
$Jacket_{total\_umber}$	Total number of jackets in the project	239
Radius	Radius of circular pile being repaired	---
$Side_1$	Dimension of the smallest side of the cross section of a rectangular pile being repaired	24 in.
$Side_2$	Dimension of the largest side of the cross section of a rectangular pile being repaired	24 in.

H.1 Quantity Equations for the Jacket Placement Module

Quantity items calculated in this example included the jacket, the number of standoffs, the volume of seam epoxy and the number of fasteners. These quantity items were listed previously in Table 6.1. Secondary parameters, default values, minimum and maximum values are listed in Table H.2, which also provides the values corresponding to the example pile. A list of the bridges as well as the number of piles considered to define default values is shown in Table H.3.

Table H.2 Default Values for Secondary Parameters Used by the Model to Calculate Jacket Quantities

Parameter	Parameter Description	Default Value	Min	Max	Example Pile
CrossID	Pile cross section type	Rectangular	---	---	Rectangular
JacketcrossID	Jacket cross section type	Rectangular	---	---	Rectangular
t_{clear}	Clearance between the jacket and the original pile	3 in.	2 in.	5 in.	2 in.
$Jacket_{length}$	Jacket length	72 in.	32 in.	258 in.	72 in.
$Jacket_{periphery}$	Periphery of the jacket under consideration	Equations H.1, H.2, H.4	---	---	112 in.
$Radius_{equivalent}$	Radius of the equivalent circle that contained the cross section of the square pile. Each corner of the square belongs to this equivalent circle.	Equation H.3	---	---	---
$Jacket_{area}$	Area of the jacket under consideration	Equation H.5	---	---	58 ft.^{2}
$Transeam_{number}$	Number of transverse seams in the jacket	Equations H.6 and H.7	---	---	0

Table H.2 (Continued)

Parameter	Parameter Description	Default Value	Min	Max	Example Pile
$Longseam_{number}$	Number of longitudinal seams in the jacket: If the jacket cross section was rectangular, used 2. If the jacket cross section was circular, used 1.	2	1	2	2
$Transeam_{overlap}$	Transverse overlap between two adjacent panels of the jacket	2 in.	2 in.	4 in.	---
$Longseam_{overlap}$	Longitudinal overlap between adjacent panels of the jacket	2 in.	2 in.	4 in.	2 in.
$Standoff_{number}$	Number of standoffs	Equations H.8, H.9, H.10	---	---	32
$Standoff_{spacing}$	Spacing of standoff pattern along jacket length	18 in.	---	---	18 in.
$Epoxy_{productivity}$	Linear feet of seam that could be sealed with one gallon of epoxy seam (includes waste)	40 (expert knowledge (Snow 1999))	35	45	40
$Longseam_{volume}$	Volume required to seal all longitudinal seams in one jacket	Equation H.11	---	---	0.3 gal
$Transeam_{volume}$	Volume required to seal all transverse seams in one jacket	Equation H.12	---	---	0.0 gal
$Fastener_{number}$	Number of fasteners placed along seams to secure them	Equation H.13	---	---	36
$Fastener_{spacing}$	Spacing of fastener along length of jacket seams	4 in.	4 in.	4 in.	4 in.

Table H.3 Number of Piles Used to Define the Default Value for a Given Bridge and Parameter

Parameter	Number of Piles	Number of Bridges	Bridge 150107	Bridge 490032	Bridge 700006	Bridge 700008	Bridge 700069	Bridge 700076	Bridge 700142	Bridge 720044	Bridge 720056	Bridge 720057	Bridge 720063
T_{clear}	1467	19	197	299	46	90	105	36	36	11	60	128	42
$Longseam_{number}$	502	18	197		46	90							42
$Longseam_{overlap}$	305	17			46	90							42
$Transeam_{number}$	869	24			46	90	105	36	36	11	60		42
$Transeam_{overlap}$	869	24			46	90	105	36	36	11	60		42
$Jacket_{length}$	1570	33	197	299	46	90	105	36	36	11	60	128	42
CrossID	1475	20	197	299	46	90	105	36	36	11	60	128	42
JacketcrossID	1570	33	197	299	46	90	105	36	36	11	60	128	42
$Jacket_{periphery}$	1570	33	197	299	46	90	105	36	36	11	60	128	42
$Standoff_{number}$	1074	26	197		46	90	105	36	36	11	60		42

Table H.3 (Continued)

Parameter	Number of Piles	Number of Bridges	Bridge 720076	Bridge 720272	Bridge 720352	Bridge 790086	Bridge 870082	Bridge 870085	Bridge 870551	Bridge 870554	Bridge 010057	Bridge 030042	Bridge 030043
CrossID	1475	20	195	49	121	32	6	4	4	6			
JacketcrossID	1570	33	195	49	121	32	6	4	4	6	1	8	12
T_{clear}	1467	19	195	49	121		6	4	4	6			
$Jacket_{length}$	1570	33	195	49	121	32	6	4	4	6	1	8	12
$Jacket_{periphery}$	1570	33	195	49	121	32	6	4	4	6	1	8	12
$Transeam_{number}$	869	24	192		121	32					1	8	12
$Longseam_{number}$	502	18				32					1	8	12
$Transeam_{overlap}$	869	24	192		121	32					1	8	12
$Longseam_{overlap}$	305	17				32					1	8	12
$Standoff_{number}$	1074	26	195		121	32					1	8	12

Table H.3 (Continued)

Parameter	Number of Piles	Number of Bridges	Bridge 030044	Bridge 030208	Bridge 120002	Bridge 130050	Bridge 130051	Bridge 170013	Bridge 170021	Bridge 170044	Bridge 170142	Bridge 170941	Bridge 700112
CrossID	1475	20											8
JacketcrossID	1570	33	16	1	8	1	6	4	19	12	5	2	8
T_{clear}	1467	19											
$Jacket_{length}$	1570	33	16	1	8	1	6	4	19	12	5	2	8
$Jacket_{periphery}$	1570	33	16	1	8	1	6	4	19	12	5	2	8
$Transeam_{number}$	869	24	16	1	8	1	6	4	19	12	5	2	
$Longseam_{number}$	502	18	16	1	8	1	6	4	19	12	5	2	
$Transeam_{overlap}$	869	24	16	1	8	1	6	4	19	12	5	2	
$Longseam_{overlap}$	502	18	16	1	8	1	6	4	19	12	5	2	
$Standoff_{number}$	1074	26	16	1	8	1	6	4	19	12	5	2	8

Jacket

The default unit price used in the model for the jacket was provided by expert knowledge as \$6.39 per square foot of fiberglass (Snow 1999) and \$4.39 per square foot of anode mesh (Daily 2004). The anode mesh was mounted on the fiberglass jacket at the factory.

To calculate the quantity of jacket material, it was necessary to determine the jacket periphery and ultimately the jacket area, which were calculated using Equations H.1 to H.5.

If both the pile and the jacket had a rectangular cross section (crossID= rectangular), (jacketcrossID = rectangular), then the jacket periphery was calculated using Equation H.1. A square pile was classified as a rectangular pile with $side_1$=$side_2$. Variables used in Equations H.1, H.2 and H.3 were defined in Table H.1.

$$\text{jacket}_{\text{periphery}} = 2 \cdot (\text{side}_1 + \text{side}_2 + 4 \cdot t_{\text{clear}}) \tag{H.1}$$

$$\text{Example pile, jacket}_{\text{periphery}} = 2 \cdot (24 + 24 + 4 \cdot 2) = 112 \text{ in.}$$

If both the pile and the jacket had a circular cross section (crossID= circular), (jacketcrossID = circular), the jacket periphery was calculated using Equation H.2.

$$\text{jacket}_{\text{periphery}} = 2 \cdot p \cdot (t_{\text{clear}} + \text{radius}) \tag{H.2}$$

If the pile had a square cross section and the jacket had a circular cross section (crossID = rectangular) (jacketcrossID = circular), the jacket periphery was calculated using the radius of a circle that circumscribed the square cross section of the pile. The radius was called equivalent radius and was calculated using Equation H.3. The jacket periphery was calculated using Equation H.4:

$$\text{radius}_{\text{equivalent}} = \frac{\text{side}_1}{\sqrt{2}} \tag{H.3}$$

$$\text{jacket}_{\text{periphery}} = 2 \cdot \text{p} \cdot \left(\text{t}_{\text{clear}} + \text{radius}_{\text{equivalent}}\right) \tag{H.4}$$

$$\begin{aligned} \text{jacket}_{\text{area}} = (&\text{periphery}_{\text{jacket}} + \text{longseam}_{\text{number}} \cdot \text{longseam}_{\text{overlap}} \\ &+ \text{transeam}_{\text{number}} \cdot \text{transeam}_{\text{overlap}}) \cdot \text{jacket}_{\text{length}} \end{aligned} \tag{H.5}$$

$$\text{Example pile, jacket}_{\text{area}} = (112 + 2 \cdot 2 + 0) = 8352\ \text{in}^2 = 58\ \text{ft}^2$$

$$\text{Jacket cost, fiberglass} = 58\ \text{ft}^2 \cdot 6.39 \frac{\text{dollars}}{\text{ft}^2} = \$370.62$$

$$\text{Jacket cost, anode mesh} = 58\ \text{ft}^2 \cdot 4.39 \frac{\text{dollars}}{\text{ft}^2} = \$254.62$$

The equations above used the pile dimensions, which were the radius dimension for either a circular pile (required parameter “radius”) or the side dimensions for a rectangular pile (required parameters “side_1”and “side_2”). The equations were applied after defining the type of cross section of the pile, which was defined by the secondary parameter “crossID” and the type of cross section of jacket, which was defined by the secondary parameter “jacketcrossID”. If the side dimension values “side_1”and “side_2” were input by the user, the model inferred that the pile was rectangular. If only one dimension was entered as “radius”, the model inferred that the pile was circular.

The default value used in the model for the secondary parameter defining the clear distance between the pile and the jacket "t_{clear}" was three inches. According to design plans of repair projects on 19 bridges and 1475 piles, the clear distance between the pile and the jacket was three inches in 48 percent of the cases, two inches in 35 percent of the cases, four inches in four percent of the cases and five inches in 13 percent of the cases.

According to design plans for the repair of 33 bridges involving 1,570 piles, the jacket side dimension varied between 16 inches to 42 inches. The mode value of the sample was 30 inches (507 cases, 32 percent). Using these values, the jacket periphery varied between 64 inches and 168 inches. The jacket periphery, based on the mode value of the sample, was 120 inches. This later value correlates well with the jacket periphery value calculated using the previous equations (112 in.).

The jacket length default value used in the model was 72 inches. This value was based on the length of the jackets used on repairs done on 33 bridges involving 1570 piles. The mode value of the sample was 72 inches. In this sample, 64 percent of the piles (1,004 piles) were repaired using a 72-inch jacket.

The width of the seam overlap used as a default value for the longitudinal seams was two inches. This value was based on design plans of repair projects involving 17 bridges and 305 piles repaired using CP jackets. In 298 of the cases (98 percent), the width of the seam was two inches, in the remaining seven cases (two percent); the width of the seam was four inches. The same default value was used for the width of the transverse seam overlap.

The number of transverse seams was defined using expert knowledge acquired during the research and data from construction projects. According to expert knowledge (Snow 1999), the maximum length of the jacket without a transverse seam was 15 feet. Jackets larger than 15 feet had one transverse seam every 10 feet. The values provided by expert knowledge were within the range observed on construction projects. From the sample used to determine the jacket length, only 42 jackets required one transverse seam. The length of jackets requiring one transverse seam varied between 150 inches and 258 inches. The length of all other jackets was less than 150 inches. A value for the number of transverse seams could be calculated using Equations H.6 and H.7:

$$15.0 \geq \text{jacket}_{\text{length}} \cdot \text{conversion}_{\text{length}} \qquad \text{transeam}_{\text{number}} = 0 \qquad \text{(H.6)}$$

$$\text{Example pile, } 15.0 > 72 \cdot \frac{1}{12} = 6\text{; therefore,} \qquad \text{transeam}_{\text{number}} = 0$$

$$\text{jacket}_{\text{length}} \cdot \text{conversion}_{\text{length}} > 15.0 \qquad \text{transeam}_{\text{number}} = \text{integer}\left(\frac{\text{jacket}_{\text{length}}}{15}\right) \text{(H.7)}$$

The parameter "$\text{conversion}_{\text{length}}$" converted the jacket length units to feet, and the function integer (x) provided the integer part of the number x.

Standoffs

The default unit price used in the model for the jackets was provided by expert knowledge as $0.10 per standoff (Snow 1999).

Jackets usually include standoffs. Standoffs were devices that were attached to the interior jacket surface to maintain adequate clearance between the existing pile and the new jacket. In general, all type of piles used fixed standoffs, except where deterioration or other causes resulted in loss of cross section. In these cases, adjustable standoffs were used to maintain proper jacket alignment. Standoffs were epoxy bonded to the interior face of the jacket by the constructor. Equations H.8 through H.10 defined the number of standoffs. Snow (1999) provided the expert knowledge used to create these equations as follows:

The standoff pattern for circular piles was the greater of six standoffs or one standoff per linear foot of periphery. The standoff pattern for a rectangular pile consisted on two standoffs equally spaced along the side of the pile. There were no standoffs in the corners.

The standoff patterns described above should be repeated every 18 feet of length of jacket.

The values provided by expert knowledge for the rectangular jackets were the same as the values observed on 26 repair projects involving 1,074 piles. In these projects, 100 percent of the jackets had two standoffs per side, equally spaced through the side of the jacket. The previous knowledge, was applied as follows:

If the cross section of the jacket was circular (jacketcrossID = circular), then:

$$\text{radius} \leq 14\ \text{in} \qquad \text{standoff}_{\text{number}} = 6 \cdot \text{integer}\ \left(\frac{\text{jacket}_{\text{length}}}{\text{standoff}_{\text{spacing}}}\right) \tag{H.8}$$

$\text{radius} > 14\ \text{in}$

$$\text{standoff}_{\text{number}} = \text{integer}\left(2 \cdot \text{p} \cdot \text{radius} \cdot \text{conversion}_{\text{length}}\right) \cdot \text{integer}\ \left(\frac{\text{jacket}_{\text{length}}}{\text{standoff}_{\text{spacing}}}\right) \tag{H.9}$$

If the jacket was rectangular, (jacketcrossID = circular), then:

$$\text{standoff}_{\text{number}} = 8 \cdot \text{integer}\ \left(\frac{\text{jacket}_{\text{length}}}{\text{standoff}_{\text{spacing}}}\right) \tag{H.10}$$

$$\text{Example pile, standoff}_{\text{number}} = 8 \cdot \text{integer}\ \left(\frac{72}{18}\right) = 32$$

$$\text{Standoff cost} = 32\ \text{standoffs} \cdot 0.10\ \frac{\text{dollars}}{\text{standoff}} = \$\ 3.2$$

Longitudinal Seam Epoxy

The default unit price used in the model for the seam epoxy was provided by expert knowledge as $13.33 per one two-gallon container of epoxy or $6.67 per gallon (Snow 1999).

This item referred to the epoxy used to seal the longitudinal seam in the jacket. According to expert knowledge, one two-gallon container of epoxy sealed approximately 75 linear feet of longitudinal seam with average material waste (Snow 1999). Thus, the default value used was rounded to 40 linear feet of longitudinal seam per gallon of epoxy with average waste (epoxy productivity=40 feet/gallon). The epoxy productivity value was based solely on expert knowledge since there were not data for this material item. The model calculated the volume (in gallons) of epoxy required for sealing the longitudinal seams using Equation H.11.

$$\text{longseam}_{\text{volume}} = \frac{\text{jacket}_{\text{length}} \cdot \text{longseam}_{\text{number}} \cdot \text{conversion}_{\text{length}}}{\text{epoxy}_{\text{productivity}}} \tag{H.11}$$

$$\text{Example pile, longseam}_{\text{volume}} = \frac{72 \cdot 2 \cdot \frac{1}{12}}{40} = 0.3 \text{ gallons}$$

$$\text{long. seam epoxy cost} = 0.3 \text{ gallons} \cdot 6.67 \frac{\text{dollars}}{\text{gallons}} = \$\ 2.01$$

<u>Transverse Seam Epoxy</u>

This item referred to epoxy used to seal the transverse seam in the jacket. The model used the same epoxy productivity value and unit price as the ones used for the longitudinal seam epoxy. The model calculated the volume (in gallons) of epoxy required for sealing the transverse seams using Equation H.12.

$$\text{transeam}_{\text{volume}} = \frac{\text{jacket}_{\text{length}} \cdot \text{transeam}_{\text{number}} \cdot \text{conversion}_{\text{length}}}{\text{epoxy}_{\text{productivity}}} \tag{H.12}$$

$$\text{Example pile, transeam}_{\text{volume}} = \frac{72 \cdot 0 \cdot \frac{1}{12}}{40} = 0.0 \text{ gallons}$$

$$\text{trans. seam epoxy cost} = 0.0 \text{ gallons} \cdot 6.67 \frac{\text{dollars}}{\text{gallon}} = \$\ 0.0$$

Jacket Fasteners

The default unit price used in the model for the jacket fasteners was provided by expert knowledge as \$0.24 per fastener (Snow 1999).

According to expert knowledge, the fastener spacing was approximately four inches along the length of the seam. This is three fasteners per linear foot of seam (Snow 1999). The number of fasteners was based solely on expert knowledge, since design plans and specifications did not provide guidelines on jacket fastener spacing. The number of fasteners was calculated using Equation H.13.

$$\text{fastener}_{\text{number}} = \text{integer}\left(\frac{\text{jacket}_{\text{length}}}{\text{fastener}_{\text{spacing}}}\right) \cdot \text{longseam}_{\text{number}} + $$

$$+ \text{integer}\left(\frac{\text{jacket}_{\text{periphery}}}{\text{fastener}_{\text{spacing}}}\right) \cdot \text{transeam}_{\text{number}} \qquad (\text{H.13})$$

$$\text{Example pile, fastener}_{\text{number}} = \text{integer}\left(\frac{72}{4}\right) \cdot 2 + 0 = 36$$

$$\text{Fasteners cost} = 36 \text{ fasteners} \cdot 0.24 \frac{\text{dollars}}{\text{fastener}} = \$\,8.64$$

Jacket Fabrication

According to expert knowledge (Snow 1999), a lump sum fee was charged to each project to account for the cost of the mold used to fabricate the jackets. This quantity was evenly divided among the number of jackets.

$$\text{Jacket fabrication cost} = \frac{610\ \text{dollars}}{235\ \text{jackets}} = \$\ 2.60\,/\,\text{Jacket}$$

Labor

According to expert knowledge (Snow 1999), labor quantities included fees for one senior technician/worker and at least one worker. Such fees were calculated as a percentage of the total linear footage of repair, but not less than one man-day. Snow (1999) recommended estimating labor quantities (man-days) as one percent of the total footage length of repair. For the example pile the total footage of repair was 1,434 feet (231 jackets 6-feet long each), 10 percent of which was approximately 14 man-days. These fees were evenly divided among the number of jackets. The default unit price used in the model for a senior technician was provided by expert knowledge as $450.00 per one man-day. Similarly, the default unit price used in the model for a worker was $150.00 per man-day. Labor fees were evenly divided among the number of jackets.

$$\text{Senior technician cost} = 14\ \text{days} \cdot 450\,\frac{\text{dollars}}{\text{day}} \cdot \frac{1}{239\ \text{jackets}} = \$\ 26.35\,/\,\text{Jacket}$$

$$\text{Worker cost} = 14\ \text{days} \cdot 150\,\frac{\text{dollars}}{\text{day}} \cdot \frac{1}{239\ \text{jackets}} = \$\ 8.79\,/\,\text{Jacket}$$

Cathodic Protection Specialist

This item included fees charged by a CP specialist while inspecting the jackets after the repair was completed. A lump sum equal to $2500.00 was evenly divided among the number of jackets.

H.2 Quantity Equations for the Continuity Bonding Module

The following example illustrates the development of equations to estimate quantities related to the Continuity Bonding Module. Required parameters were the same as those used in Example H.1 and were listed in Table H.1. Table H.4 lists secondary parameters and default values used by the model. Table H.5 lists the number of observations for a given bridge and parameter which made up the sample.

Before the constructor installed a CP jacket, it was necessary to assure that all the reinforcement in the piles were continuous. Inspection data from bridges 720063, 720076, and 790086 involving the repair of 155 reinforced concrete piles showed that mild steel bars in reinforced concrete piles were always continuous. However, steel prestressing strands in prestressed piles were sometimes discontinuous. In all CP installations, quality control specifications required that the contractor recorded in a standard format the potential difference between one prestressing strand, selected as the ground location, and each other prestressing strand for each pile being repaired (Corrpro 1999). When a prestressing strand was discontinuous, the potential difference was greater than zero. This measurement was used to identify discontinuous prestressing strands in the pile and its location. When prestressing strands were discontinuous, they were made continuous by bonding the discontinuous prestressing strands to a continuous one with a piece of metal. The process was called continuity bonding and required the excavation of the concrete surrounding the discontinuous prestressing strands. Therefore, once discontinuous prestressing strands and its location were identified, it was possible to determine the number of continuity excavations that needed to be performed on the pile. The model used data from the quality control reports filled by contractors for 11 bridges and 451 prestressed concrete piles to estimate the empirical probability of a pile requiring a continuity excavation and the empirical probability of having a given number of discontinuous prestressing strands in a continuity excavation.

Table H.4. Default Values for Secondary Parameters Used by the Model to Calculate Continuity Bonding Quantities

Parameter	Parameter Description	Default Value	Min	Max	Example Pile
$Contexcav_{maxn}$	Maximum number of continuity excavations in one pile	Table H.6	---	---	4
n	Number of continuity excavations in one pile	0,1… $contexcav_{maxn}$	---	---	0, 1, 2, 3, 4
Ex_prob_n	Empirical probability that a pile requires "n" continuity excavations	Table H.7	---	---	ex_prob_0= 0.71 ex_prob_1= 0.14 ex_prob_2= 0.07 ex_prob_3= 0.06 ex_prob_4= 0.02
$Numpilex_n$	Number of piles requiring "n"continuity excavations	Equation H.14	---	---	$numpilex_0$=170 $numpilex_2$= 33 $numpilex_3$= 17 $numpilex_4$= 14 $numpilex_5$= 5
$Contexcav_{total}$	Total number of continuity excavations	Equation H.15	---	---	129
m	Number of discontinuous strands in one excavation	1, 2…. …$strand_{maxdisc}$	---	---	1, 2, 3, 4
$Strand_{maxdisc}$	Maximum number of discontinuous strands in one excavation	4	---	---	4
$Dispob_m$	Empirical probability that a continuity excavation involves "m" discontinuous strands	Table H.8	---	---	$disprob_1$= 0.59 $disprob_2$= 0.26 $disprob_3$= 0.12 $disprob_4$= 0.03
$Numex_m$	Number of excavations showing "m" discontinuous strands	Equation H.16	---	----	$numex_1$=76 $numex_2$=34 $numex_3$=15 $numex_4$= 4

Table H.4. (Continued)

Parameter	Parameter Description	Default Value	Min	Max	Example Pile
$Strand_{cc}$	Center-to-center distance between strands	Equation H.17 & Equation H.18	---	---	4.5 in.
$Strand_{number}$	Number of strands in one pile	16 strands	12	20	16
Cover	Concrete cover for longi-tudinal reinforcement	3 in.	2 in.	3.75 in.	3 in.
$Pile_{periphery}$	Pile periphery	Equation H.19 & Equation H.20	---	---.	94 in.
$Pile_{area}$	Pile area	Equation H.21 & Equation H.22	---	---	576 in.^{2}
$Contexcav_{height}$	Height of the continuity excavation	4 in.	2 in.	4 in.	4 in.
$Contexcav_{widthm}$	Width of a continuity excavation involving “m” discontinuous prestressing strands	Equation H.23	---.	---	---
$Length_{cutting}$	Length of concrete to be cut for continuity excava-tions	Equation H.24	---	---	1.4 ft.
$Contexcav_{totalvol}$	Total excavation volume required for continuity bonding	Equation H.25	---	---	0.04 ft.^{2}

Table H.5 Bridges Used to Define the Default Value for a Given Bridge and Parameter

Parameter	Number of Piles	Number of Bridges	Bridge 150107	Bridge 490032	Bridge 700006	Bridge 700008	Bridge 700069	Bridge 700076	Bridge 700142	Bridge 720044	Bridge 720056	Bridge 720057
$Strand_{number}$	1216	14		299	46	90	105	36	36	11	60	128
Cover	1167	13		299	46	90	105	36	36	11	60	128
$Side_i$	1475	20	197	299	46	90	105	36	36	11	60	128
N	451	11			46	70	93	18	18			42
M	451	11			46	70	93	18	18			42
$Contexcav_{height}$	1066	16	197		46	90	105	36	36	11		128

Table H.5 (Continued)

Parameter	Bridge 720063	Bridge 720076	Bridge 720272	Bridge 720352	Bridge 790086	Bridge 870082	Bridge 870085	Bridge 870551	Bridge 870554	Bridge 460072	Bridge 490003	Bridge 700112
$Strand_{number}$		195	49	121	32							8
Cover		195		121	32							8
$Side_i$	42	195	49	121	32	6	5	4	6			8
N				66	32					49	9	8
M				66	32					49	9	8
$Contexcav_{height}$		195	49	121	32	6	4	4				

To estimate the continuity bonding material quantities it was necessary to calculate the number of continuity excavations and the size of the excavation. The size of the excavation was calculated based on the number of discontinuous prestressing strands and the center-to-center distance between prestressing strands.

<u>Number of Excavations</u>

The maximum number of excavations in one pile depended on the type of cross section of the pile. Table H.6 lists the maximum number of excavations, defined by the secondary parameter $contexcav_{maxn}$. As an example, a pile with a rectangular cross section could have a maximum of four excavations in one pile or one excavation per face.

The number of excavations required for continuity bonding did not depend on the condition state of the element. Table H.7 shows the empirical probability of rectangular piles showing discontinuous prestressing strands on one, two, three, or four faces. The parameter "ex_prob_n" represented the empirical probability of a rectangular pile having "n" number of excavations. These empirical probabilities were based on a sample of 451 bridge piles repaired on 11 bridges in Florida.

Table H.6 Maximum Number of Excavations in One Pile

Cross section	$Contexcav_{maxn}$
Circular	2
Rectangular	4

Table H.7 Empirical Probabilities of Pile Requiring Continuity Bonding due to Discontinuous Prestressing Strands in One, Two, Three, or Four Faces

Number of Piles	Number of Excavation per Pile "n"	Empirical Probability	Approximate Empirical Probability Used by the Model "ex_probn"
322	0	0.714	0.71
62	1	0.137	0.14
33	2	0.073	0.07
27	3	0.060	0.06
7	4	0.016	0.02

The number of piles ($numpilex_n$) requiring "n" continuity excavation could be calculated using Equation H.14. The total number of continuity excavations was defined by the parameter "$contexcav_{total}$" and Equation H.15. The function int(x) rounds the number "x" to the nearest integer.

$$numpilex_n = int(ex\_prob_n \cdot jacket_{tot\_number}) \tag{H.14}$$

$$contexcav_{total} = \sum_{n=1}^{contexcav_{max\,n}} numpilex_n \cdot n \tag{H.15}$$

Equations H.14 and H.15 generate the branches of a probability tree. Considering the example pile (pile 6 on span 6 of the Howard Frankland Bridge (Bridge No. 150107)), the total number of jackets that were installed in the project in which the example pile was repaired was 239. The model defined the number of piles requiring none, one, two, three or four excavations using Equation H.14 as follows:

- Number of piles requiring no excavation:

  $Numpilex_0$ = int (ex_prob_0 . $jacket_{tot\_number}$)= int (.71)(239) =170 piles

- Number of piles requiring one excavation:

  $Numpilex_1$ = int (ex_prob_1 . $jacket_{tot\_number}$)= int (.14)(239) =33 piles

- Number of piles requiring two excavations:

  $Numpilex_2$ = int (ex_prob_2 . $jacket_{tot\_number}$)= int (.07)(239) =17 piles

- Number of piles requiring three excavations:

  $Numpilex_3$ = int (ex_prob_3 . $jacket_{tot\_number}$)= int (.06)(239) =14 piles

- Number of piles requiring four excavations:

  $Numpilex_4$ = int (ex_prob_4 . $jacket_{tot\_number}$)= int (.02)(239) = 5 piles

The total number of excavations was calculated using Equation H.15 as follows:

$$\text{contexca}_{\text{total}} = (0 \cdot 170) + (1 \cdot 33) + (2 \cdot 17) + (3.14) + (4 \cdot 5) = 129$$

<u>Size of Continuity Excavations</u>

The size of the excavation depended on the number of discontinuous prestressing strands and the center-to-center distance between the prestressing strands.

Number of Discontinuous Prestressing Strands in one Excavation

Table H.8 shows the empirical probability that one excavation had one, two, three or four discontinuous prestressing strands. The parameter "$disprob_m$" represented the empirical probability that one excavation had "m" discontinuous prestressing strands.

The number of excavations showing “m” discontinuous prestressing strands was calculated using the empirical probabilities listed in Table H.8 and Equation H.16 as follows:

$$numex_m = int(disprob_m \cdot contexcav_{total}) \qquad (H.16)$$

Table H.8 Empirical Probability that One Excavation had One, Two, Three or Four Discontinuous Prestressing Strands

Number of Excavations	Number of Discontinuous Prestressing Strands per Excavation “m”	Empirical Probability	Approximate Empirical Probability Used by the Model “$disprob_m$”
139	1	0.589	0.59
62	2	0.263	0.26
29	3	0.123	0.12
6	4	0.025	0.03

Recalling that the total number of continuity excavations was estimated previously as 126 excavations for the example under consideration, the model defined the number of excavations with one, two, three or four discontinuous prestressing strands using Equation H.16 as follows:

- Number of continuity excavations involving one discontinuous prestressing strand:

  $Numex_1$ = int ($disprob_1$. $contexcav_{total}$)= int ((.59)(129)) = 76 excavations

- Number of continuity excavations involving two discontinuous prestressing strands:

  $Numex_2$ = int ($disprob_2$. $contexcav_{total}$)= int ((.26)(129)) = 34 excavations

- Number of continuity excavations involving three discontinuous prestressing strands:

  $Numex_3$ = int ($disprob_3$. $contexcav_{total}$)= int ((.12)(129)) = 15 excavations

- Number of continuity excavations involving four discontinuous prestressing strands:

  $Numex_4$ = int ($disprob_4$. $contexcav_{total}$)= int ((.03)(129)) = 4 excavations

Center- to-Center Distance Between Prestressing Strands

For rectangular piles, the center-to-center distance between prestressing strands was calculated using Equation H.17. For circular piles, the center-to-center spacing was calculated using Equation H.18.

$$\text{strand}_{\text{cc}} = \frac{\text{pile}_{\text{periphery}} - 8 \cdot \text{cover}}{\text{strand}_{\text{number}}} \qquad \text{(H.17)}$$

$$\text{strand}_{\text{cc}} = \frac{\text{pile}_{\text{periphery}} - 2 \cdot \pi \cdot \text{cover}}{\text{strand}_{\text{number}}} \qquad \text{(H.18)}$$

The pile periphery for rectangular piles was defined by Equation H.19, and for circular piles was defined by Equation H.20. Similarly, for rectangular piles, the area of the pile cross section was defined by Equation H.21, and for circular piles, was defined by Equation H.22.

$$\text{pile}_{\text{periphery}} = 2 \cdot (\text{side}_1 + \text{side}_2) \qquad \text{(H.19)}$$

$$\text{pile}_{\text{periphery}} = 2 \cdot \pi \cdot \text{radius} \qquad \text{(H.20)}$$

$$pile_{area} = side_1 \cdot side_2 \tag{H.21}$$

$$pile_{area} = \frac{\pi \cdot radius^2}{2} \tag{H.22}$$

The default value for the reinforcement cover given by the parameter "cover" was three inches. This value was based on FDOT design plans corresponding to 13 projects and 1,167 piles. In the sample, 56 percent of the piles had a reinforcement cover equal to three inches. The default value used in the model for the number of prestressing strands in a prestressed pile ("$strand_{number}$") was 16. This default value was based on FDOT design plans corresponding to 14 projects and 1,216 piles. In the sample, 48 percent of the piles had 16 prestressing strands. The second most common value (48 percent) was 20 prestressing strands per pile.

Considering the previous example and knowing that the bridge piles were square and the side dimension of the pile cross section was 24 inches, the pile periphery, pile area, number of prestressing strands and center-to-center distance between prestressing strands could be calculated as follows:

From Equation H.19	$pile_{periphery} = 2\,(24 + 24) = 96$
From Equation H.21	$pile_{area} = (24)\,(24) = 576$

Therefore, the prestressing strand center-to-center distance could be calculated from Equation H.17 as follows:

$$\text{strand}_{cc} = \frac{96 - 8 \cdot 3}{16} = 4.5 \text{ in.}$$

The model used the pile periphery, pile area, number of prestressing strands and center-to-center distance between prestressing strands, discussed in the previous section, to calculate the quantity items related to continuity bonding. These material quantity items were listed in Table 6.1 and included: concrete cutting, volume of continuity excavation, continuity connections, continuity wire, negative connection wire, continuity welds, epoxy volume and grout volume. Each material quantity item is discussed below.

Concrete Cutting

This quantity item referred to the length of concrete to be cut before removing the concrete to perform the continuity bonding of the prestressing strands. This length depended on the width and height of the continuity excavation. The width of a continuity excavation involving "m" discontinuous prestressing strands ("$\text{contexcav}_{\text{widthm}}$") was calculated using Equation H.23, and the total length of concrete that was cut was calculated using Equation H.24.

$$\text{contexcav}_{\text{widthm}} = \sum_{m=1}^{\text{strnad}_{\text{max disc}}} \text{numex}_m \cdot (m+1) \cdot \text{strand}_{cc} \qquad \text{(H.23)}$$

$$\text{length}_{\text{cutting}} = 2.(\text{contexcav}_{\text{widthm}}) + 2 \cdot (\text{contexcav}_{\text{total}} \cdot \text{contexcav}_{\text{height}}) \qquad \text{(H.24)}$$

The default value for the height of the continuity excavation, defined by the parameter "$contexcav_{height}$", was four inches. This value was based on design plans for FDOT projects involving the repair of 16 bridges and 1,066 piles. In 64 percent of the cases, the height of the continuity excavation was four inches. In the remaining cases, the height of the continuity excavation was two inches.

For a rectangular pile, the maximum number of continuity excavations, defined by the variable "$contexcav_{maxn}$", was four. In addition, by default, the number of prestressing strands was 16. The parameter "$numex_{m}$", calculated previously, represented the number of continuity excavations involving "m" discontinuous prestressing strands. The prestressing strand center-to-center distance parameter was calculated previously as four and a half inches. Equation H.23 was a sum of series that calculated the length of concrete cutting along the width of the continuity excavations for excavations involving "m" discontinuous prestressing strands. Considering the example described in the previous section and applying the values calculated previously, Table H.9 shows the results corresponding to each term of the sum of series shown in Equation H.23.

Table H.9 Width of the Continuity Excavations for a Given Number of Discontinuous Prestressing Strands "m"

Number of Discontinuous Prestressing Strands "m"	Number of Excavations with "m" Discontinuous Prestressing Strands ("$numex_m$")	Width of One Continuity Excavation with "m" Discontinuous Prestressing Strands [(m+1) $strand_{cc}$]	Total Width of Concrete Cutting [$numex_m$(m+1) $strand_{cc}$]
1	76	4.5 (1+1) = 9.0	76 (9.0) = 666.0
2	34	4.5 (2+1) = 13.5	34 (13.5) = 445.5
3	15	4.5 (3+1) = 18.0	15 (18.0) = 270.0
4	4	4.5 (4+1) = 22.5	4 (22.5) = 90.0

$$\text{contexcav}_{\text{widthm}} = \sum_{m=1}^{\text{strnad}_{\text{max disc}}} \text{numex}_m \cdot (m+1) \cdot \text{strand}_{\text{separation}} = 684 + 459 + 270 + 90 = 1503 \text{ in.}$$

The second part of Equation H.24 was the length of concrete cutting along the height of the excavation. Using the values calculated in Table H.9, recalling that the total number of excavations in the example considered was 126 excavations, and knowing that the default value for the height of the continuity excavation was four inches, Equation H.24 results in the following:

$$\text{length}_{\text{cutting}} = 2 \cdot 1503 + 2 \cdot 129 \cdot 4 = 4038 \text{ inches} = 337 \text{ feet}$$

The length of concrete cutting assigned to the example pile was a fraction of the total quantity, as follows:

$$\text{Average length of concrete cutting per jacket} = \frac{1}{239} \cdot 337 \text{ feet} = 1.4 \text{ feet}$$

<u>Concrete Removal, Continuity Excavation</u>

This quantity item referred to the volume that was removed from the pile in order to perform the continuity bonding and was defined by the parameter “$\text{contexcav}_{\text{totalvol}}$”. This quantity item was calculated using Equation H.25, as follows:

$$\text{contexcav}_{\text{totalvol}} = \left(\sum_{m=1}^{\text{strand maxdisc}} \text{numex}_m \cdot (m+1) \cdot \text{strand}_{cc} \right) \cdot \text{contexcav}_{\text{height}} \cdot \text{cover} \qquad \text{(H.25)}$$

Using the numbers calculated previously and recalling that the default value for the variable “cover” was three inches, the total volume of concrete to be removed was:

$$\text{contexcav}_{\text{totalvol}} = 1503 \cdot 4 \cdot 3 = 18036 \text{ in}^3 = 10.4 \text{ ft}^3$$

The volume of concrete removed due to continuity bonding for the example pile was a fraction of the total quantity, as follows:

Average volume of concrete removal for continuity excavations per jacket =

$$= \frac{1}{239} \cdot 10.4\ \text{ft}^3 = 0.04\ \text{ft}^3$$

<u>Connections, Continuity Bonding</u>

This quantity item referred to the number of continuity bonding connections, and it was given by the parameter “$\text{connection}_{\text{total}}$”. The number of continuity bonding connections was always equal to the number of discontinuous prestressing strands plus one because discontinuous prestressing strands need to be connected to one continuous prestressing strand. This quantity item was calculated using Equation H.26, as follows:

$$\text{connection}_{\text{total}} = \sum_{m=1}^{\text{strand}_{\text{max disc}}} \text{numex}_m \cdot (m+1) \tag{H.26}$$

Table H.10 shows the results corresponding to each term of the sum of series shown in Equation H.26.

Table H.10 Number of Continuity Connections for a Given Number of Discontinuous Prestressing Strands "m"

Number of Discontinuous Prestressing Strands "m"	Number of Excavations with "m" Discontinuous Prestressing Strands ("$numex_m$")	Number of Connections Involving "m" Discontinuous Prestressing Strands. [$numex_m \cdot (m+1)$]
1	76	76 (1+1) = 152
2	34	34 (2+1) = 102
3	15	15 (3+1) = 60
4	4	4 (4+1) = 20
$connection_{total} = \sum_{m=1}^{strnad_{max\ disc}} numex_m \cdot (m+1) = 152 + 102 + 60 + 20 = 334$		

The number of continuity connections for the example pile was a fraction of the total quantity, as follows:

$$\text{Average number of continuity connections per jacket} = \frac{1}{239} \cdot 334 = 1.4$$

Continuity Wire

This quantity item referred to the length of continuity wire required for the continuity bonding of the prestressing strands, and it was calculated using Equation H.27. The length of the continuity wire was equal to the total width of concrete cutting calculated for the continuity excavations Equation H.23, thus:

$$\text{continuity wire} = \text{contexcav}_{\text{widthm}} \tag{H.27}$$

For the example pile, the length of continuity wire was:

$$\text{Average length of continuity wire per jacket} = \frac{1}{239} \cdot 1503 = 6.3\ \text{in.} = 0.5\ \text{ft.}$$

Negative Connection Wire

This quantity item referred to the length of the negative connection wire. The negative connection was made within the limits of the jacket, and it extended to the top of the jacket, therefore the length of negative connection wire required was assumed to be equal to the length of the jacket.

$$\text{negative connection wire} = \text{jacket}_{\text{length}} \tag{H.28}$$

For the example pile, the length of the negative connection wire was 72 inches or six feet.

Negative Connection Weld

Since there was one negative connection per jacket, the number of negative connection welds per jacket was one.

Epoxy Volume, Connections

By default, the volume of epoxy required to cover one continuity connection was 0.1 inch^3 of epoxy. Therefore, the epoxy volume required to cover the continuity connections was calculated using Equation H.29:

$$\text{epoxy}_{\text{weldvol}} = 0.1 \cdot \text{connection}_{\text{total}} \tag{H.29}$$

For the example pile,

Volume of epoxy per jacket used to cover welds = $\frac{1}{239} \cdot 0.1 \cdot (334) = 0.14 \cdot \text{in}^3$

<u>Grout Volume, Continuity Bonding</u>

The total grout volume was calculated using Equation H.30. The total grout volume required to restore the continuity bonding excavations to their original profile was equal to the volume removed, which was defined previously by Equation H.25.

$$\text{grout volume} = \text{contexcav}_{\text{totalvol}} \qquad \text{(H.30)}$$

For the example pile,

Average grout volume per jacket used to restore continuity excavations =

$$= \frac{1}{239} \cdot 10.4 \text{ ft}^3 = 0.04 \text{ ft}^3$$

APPENDIX I

PRODUCTIVITY FACTORS

Duration of construction activities and productivity factors for underwater activities were determined from a survey conducted among 11 Navy divers, from the Underwater Construction Team One, at the Naval Amphibious Base in Norfolk, Virginia. A typical survey was included in Appendix J. Civilian divers did not validate the survey results.

The author recommends conducting a second survey, which may include divers from different backgrounds, as future research.

I.1 <u>Duration of Underwater Construction Activities</u>

At the time of the survey, the underwater construction experience of the divers participating in the survey varied between one and 20 years as follows:

- Four divers had more than one year but less than five years
- Three divers had more than five years but less than ten years
- Three divers had more than ten years but less than 15
- One diver had more than 15 years but less than 20 years

In the survey, the duration of underwater construction activities is reported in terms of average, maximum and minimum duration. The average duration is defined as the typical duration of an activity assuming that the productivity of the diver is not affected by adverse factors. The minimum and maximum duration of the underwater construction activities provide a range for each activity. The average, minimum and maximum duration of each underwater construction activity used in the model are the respective average values reported by the divers in the survey and are listed in Table I.1.

Table I.1 Duration of Underwater Construction Activities

Task	Task ID	Subtask Definition	Sub-task ID	Section ID	Generic Duration (min)			Unit
					Avg	Max	Min	
Concrete Removal	CR	Sound test concrete area	3	3	4	12	2	ft^2
	CR	Remove large pieces of unsound concrete	4	3	12	36	6	ft^3
	CR	Remove loose particles and remaining unsound concrete	5	3	11	36	6	ft^2
	CR	Clean pile surface	7	3	5	13	2	ft^2
	CR	Saw cut concrete to make a small excavation	8	3	34	58	17	ft
Reinforce-ment Repair	RR	Clean reinforcement	1	3	13	26	9	each
	RR	Place steel mesh around pile	3	3	24	50	17	each
	RR	Place rebar cage around pile	5	3	44	78	38	each
	RR	Weld steel mesh	6	3	46	73	28	each
	RR	Place additional rebar at proper location	7	3	40	73	32	each
	RR	Weld additional rebar to pile reinforcement (*)	8	3	90	60	46	each

Table I.1 (Continued)

Task	Task ID	Subtask Definition	Sub-task ID	Generic Duration (min)			Unit
				Avg	Max	Min	
Formwork Placement	FP	Install bottom formwork (*)	3	136	185	82	each
	FP	Install lateral formwork	4	95	180	78	each
	FP	Install lateral braces (*)	5	146	180	78	each
Excavation	EX	Excavate sand below mudline	2	28	62	23	ft^3
	EX	Excavate coarse soil below mudline	2	37	73	33	each
	EX	Excavate clay below mudline	2	49	114	41	ft^3
Jacket Placement	JP	Apply epoxy to jacket seams	4	35	95	33	ft
	JP	Insert jacket fasteners (*)	6	23	79	24	each
	JP	Place jacket at proper elevation	3	43	67	25	each

Table I.1 (Continued)

Task	Task ID	Subtask Definition	Sub-task ID	Generic Duration (min)			Unit
				Avg.	Max	Min	
Grout Casting	GC	Pump bottom seal (*)	8	60	78	33	ft^3
	GC	Move to upper injection port(*)	11	52	53	31	each
	GC	Place grout hose at the bottom of the jacket (*)	12	47	73	35	each
Formwork Removal	FR	Remove bottom formwork (*)	1	86	97	32	each
	FR	Remove lateral braces (*)	2	45	66	28	each
	FR	Remove lateral formwork (*)	3	87	98	33	each
Concrete Reinforcement Patching	CP	Restore small excavations to original profile	3	27	50	22	ft^3

The average of the average value provided by the divers for activities marked with an asterisk (*) were outside the limits set by the maximum and minimum values provided in the sample, and therefore were considered inconsistent. To overcome such a problem, the average value listed in Table I.1 for the items marked with an asterisk was the average of all values.

I.2 Factors Affecting the Duration of Underwater Construction Activities

The duration of underwater construction activities listed in Table I.1 are modified by productivity factors based on the water current, visibility, water temperature and water pressure (depth). The survey provides specific ranges to classify each one of the productivity factors listed above. The ranges are defined according to the guidelines provided by the U.S. Navy Diving Manual, the U.S. Army Corps of Engineers Safety and Health Requirement Manual and the Occupational Safety and Health Administration U.S. Department of Labor (OSHA). For each one of the factors affecting the productivity of divers, results of the survey include the following:

- Validation of ranges used to classify each productivity factor
- If the diver did not agree with the ranges provided, the diver was asked to provide an alternative range
- Validation of a perceived reduction in productivity due to the factors analyzed
- Definition of an average, maximum and minimum productivity percentage for each factor if the diver agrees that the factor affects the duration of underwater construction activities

Survey results for each factor are discussed in detail in the following pages.

Water Current

The water current was classified into four ranges as follows:

- Low current – less than or equal to one knot
- Medium current – greater than one knot but less than or equal to one and a half (1.5) knots

- High current – greater than one and a half (1.5) knots but less than or equal to two and a half (2.5) knots
- Extremely high current – greater than two and a half (2.5) knots

The above classification was based on the equipment requirements for working in currents. Both OSHA and the U.S. Army Corp of Engineers guidelines stated that divers could use scuba diving equipment up to one knot. According to the U.S. Navy Diving Manual, a diver wearing a surface supplied outfit could usually work in currents up to one and a half (1.5) knots without undue difficulty. A diver supplied with an additional weight belt might be able to work in currents as strong as two and a half (2.5) knots.

According to the results of the survey, 100 percent of the Navy Divers agreed that water current affected their productivity. The reasons given by divers to explain the decrease in productivity included (1) current caused divers to have a harder time managing tools and material while working, (2) diver movements were limited by current, (3) positioning of diver and material around the pile took longer, (4) divers got tired faster as water current increased.

Seventy-three percent of the divers agreed that the range used to classify current was appropriate. The modified range proposed by the divers, who disagreed with the classification, set the lower limit of current at 0.5 knot and the upper limit (extremely high current) at 1.5 knots. A summary of the productivity average values for each one of the water current ranges is shown in Table I.2.

Table I.2 Water Current Productivity Factors for Underwater Activities

Water Current Classification	Average Productivity	Maximum Productivity	Minimum Productivity
Low current	0.90	0.99	0.81
Medium current	0.78	0.89	0.63
High current	0.57	0.70	0.35
Extremely high current	0.36	0.50	0.21

Visibility

The visibility is classified into three ranges as follows:

- Good visibility – greater than three feet
- Medium visibility – greater than one foot but less than or equal to three feet
- Poor visibility – less than or equal to one foot

Visibility could influence the selection of the dive technique and could increase the time required for a diver to complete a task. The U.S. Army Corps of Engineers guidelines stated that scuba diving equipment could only be used when the visibility is more than three feet. If visibility was less than three feet, the diver should be line tended with diver/surface two-way voice communications. One-hundred percent of the divers participating in the survey agreed both that visibility affected their productivity and that the ranges used to classify visibility were appropriate. According to the divers, productivity decreased with visibility because divers had to rely on "feeling" the damage by touching the surface of the pile rather than a visual inspection.

A summary of the productivity average values for each one of the visibility ranges is shown in Table I.3.

Table I.3 Visibility Productivity Factors for Underwater Activities

Visibility Classification	Average Productivity	Maximum Productivity	Minimum Productivity
Good visibility	0.89	0.93	0.76
Medium visibility	0.76	0.85	0.63
Poor visibility	0.53	0.64	0.44

<u>Water Temperature</u>

The water temperature is classified in the following ranges:

- Warm water – greater than or equal to 80 ^{o}F
- Moderate water – less than 80 ^{o}F but greater than or equal to 65 ^{o}F
- Cold water – less than 65 ^{o}F but greater than or equal to 40 ^{o}F
- Very cold water – less than 40 ^{o}F

The water temperature ranges were based on the diver's thermal protection gear requirements at different temperatures. The U.S. Navy Diving Manual stated that a diver could be unprotected at temperatures greater or equal to 80 ^{o}F. Productivity decreases in hot water due to diver overheating. If a diver overheats, he needs to chill above water for between one to two hours. A wet suit is required for temperatures between 80 ^{o}F and 65 ^{o}F. Within this temperature range (moderate temperature) thermal protection is not the limiting factor in the dive duration. At water temperatures between 65 ^{o}F and 40^{o}F, divers must wear a dry suit and can stay underwater for a maximum time of five hours. A hot water suit is required when water temperatures drop below 40 ^{o}F, and the maximum dive time is reduced to one hour. According to the divers' personal experience, productivity decreases with lower temperatures because they are switched out more frequently when it is cold. In addition, the diver's body stops responding properly when placed outside its comfort zone.

According to the survey results, 73 percent of the divers agreed that water temperature affected their productivity. The same percentage of divers agreed that the ranges used to classify water temperature were appropriate. Divers, who disagreed with the ranges used in the survey, proposed ranges within 5 to 10 ^{o}F of those used in the model. A summary of the productivity average values for each one of the water current ranges is shown in Table I.4.

Table I.4 Water Temperature Productivity Factors for Underwater Activities

Water Temperature Classification	Average Productivity	Maximum Productivity	Minimum Productivity
Warm water	0.83	0.97	0.84
Moderate water	0.88	0.94	0.76
Cold water	0.71	0.80	0.56
Very cold water	0.53	0.60	0.39

<u>Water Pressure</u>

Water pressure is classified into four pressure ranges:

- Low pressure – less than or equal to 60 fsw (feet of seawater)
- Moderate pressure – less than or equal to 130 fsw but greater than 60 fsw
- High pressure – less than or equal to 190 fsw but greater than 130 fsw
- Very high pressure – less than or equal to 285 fsw but greater than 190 fsw

The ranges used to classify the water pressure are based on air diving equipment limitations for each range. According to the U.S. Navy Diving Manual, the pressure limit for divers using scuba diving equipment with a single bottle and without an emergency gas supply (EGS) is 60 fsw. This limit is extended to 130 fsw if divers are using an EGS. OSHA also sets the maximum pressure limit for using scuba equipment at 130 fsw. According to OSHA, 190 fsw is the pressure limit when using surface-supplied air diving equipment. Within the high pressure range (130 fsw to 190 fsw) a decompression chamber is required on site and divers are required to have an EGS. According to the U.S. Navy Diving Manual, U.S. Navy divers are allowed to use hardhat surface-supplied air diving equipment with EGS up to 285 fsw in extraordinary situations.

Fifty-five percent of the divers agreed that pressure affected their productivity. Eighty percent of the divers agreed that the ranges provided in the survey to classify water pressure were appropriate. Divers, who disagreed with the ranges proposed in the survey, defined the upper limit of moderate pressure and the lower limit of high pressure at 100 fsw instead of a 130 fsw. All the other limits remained the same. Divers attribute the decrease in productivity at greater water pressure to the increased risk of narcosis and the extended amount of time it takes to bring equipment and materials from the surface. Also, divers report a decrease in productivity due to the type of gear worn.

A summary of the productivity average values for each one of the water pressure ranges is shown in Table I.5.

Table I.5 Water Pressure Productivity Factors for Underwater Activities

Water Pressure Classification	Average Productivity	Maximum Productivity	Minimum Productivity
Low pressure	0.93	0.98	0.79
Moderate pressure	0.84	0.93	0.74
High pressure	0.75	0.87	0.61
Very high pressure	0.68	0.76	0.47

All divers participating in the survey agreed that when encountering a combination of factors of current speed, visibility, water temperature and water pressure, the effect of such factors was purely additive and independent of each other. In other words, the combined effect of more than one factor is given by the sum of the reduction in productivity of each independent factor.

I.3 Factors Affecting the Duration of Construction Activities above Water

Temperature, Relative Humidity and Wind

Labor correction factors based on temperature and relative humidity are listed in Table I.6. Table I.6 was provided by Mechanical City, a contractor specialized in the field of bridge repair. According to Means (1990), the actual temperature should be adjusted to an equivalent temperature based on wind conditions, see Table I.7.

Table I.6 Labor Correction Factors due to Temperature and Humidity

		Temperature (°F)														
		-20	-10	0	10	20	30	40	50	70	90	95	100	105	110	115
Relative humidity	95	--	--	--	1.65	1.45	1.25	1.10	1.00	.92	1.10	1.20	--	--	--	--
	90	--	--	1.80	1.60	1.42	1.23	1.09	1.00	.90	1.08	1.17	--	--	--	--
	85	--	2.00	1.70	1.55	1.39	1.21	.99	.99	.90	1.06	1.15	--	--	--	--
	80	3.00	1.95	1.60	1.51	1.36	1.19	.99	.99	.90	1.04	1.13	1.40	--	--	--
	75	2.80	1.90	1.55	1.48	1.31	1.17	.98	.98	.90	1.02	1.10	1.36	--	--	--
	70	2.65	1.85	1.50	1.45	1.30	1.15	.98	.98	.90	1.00	1.07	1.32	--	--	--
	60	2.50	1.81	1.47	1.42	1.27	1.13	.97	.97	.90	.98	1.05	1.30	1.65	--	--
	50	2.35	1.77	1.45	1.39	1.24	1.11	.96	.96	.90	.97	1.02	1.24	1.50	1.80	--
	40	2.20	1.73	1.42	1.36	1.21	1.09	.96	.96	.90	.96	1.00	1.16	1.30	1.55	2.00
	30	2.10	1.69	1.40	1.33	1.18	1.07	.95	.95	.90	.95	.98	1.05	1.12	1.34	1.55
	20	2.00	1.65	1.32	1.30	1.15	1.05	.95	.95	.90	.94	.96	.98	1.02	1.08	1.20

(Table provided by Ted Gibson, Fax, April 28, 1999)

Table I.7 Wind Chill Factors

Wind Speed M.P.H.	Actual Thermometer Reading (^{o}F)										
	50	40	30	20	10	0	-10	-20	-30	-40	-50
	Equivalent Temperature (^{o}F)										
0	50	40	30	20	10	0	-10	-20	-30	-40	-50
5	48	37	27	16	6	-5	-15	-26	-36	-47	-57
10	40	29	16	-4	-9	-21	-33	-46	-58	-70	-83
15	36	22	9	-5	-18	-36	-46	-58	-70	-85	-99
20	32	18		-10	-25	-39	-53	-67	-82	-96	-110
25	30	16		-15	-29	-44	-59	-74	-88	-104	-113
30	28	13		-18	-33	-48	-63	-79	-94	-109	-123
35	27	11		-20	-35	-49	-67	-82	-98	-113	-129
40	26	10		-21	-37	-53	-69	-85	-100	-116	-132
Winds Greater than 40 M.P.H. have little additional effect	Little danger for properly clothed person				Increasing danger from freezing of exposed flesh			Greater danger from freezing of exposed flesh			

(Used by permission of RS Means Company, Inc., Table was Modified)[1]

Pile Cap Elevation

The pile cap elevation also triggered the use of a productivity factor. The rationale behind this productivity factor was that the continuity bonding should be done one foot below the pile cap interface if three or more strands were discontinuous. Thus, as

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[1] From Means Estimating Handbook, 1990. Copyright Reed Construction Data, Kingston, MA 781-585-7880; All rights reserved.

the pile elevation increased, labor productivity decreased for installations higher than 15 feet (Means 1990). The duration of the construction activities were increased by 10 percent for each additional five feet, above15 feet measured from the MLW if the bridge was underwater or 15 feet measured from the ground elevation if the bridge was not underwater. The productivity factors shown in Table I.8 were based on productivity charts published by Means (1990) that accounted for labor cost increases for installations of piping at heights other than 15 feet. Such productivity factors were not specific to repair of bridges. The author recommends, as future research, to validate the productivity factors proposed in Table I.8.

Economy of Scale for Electrical Installations

A deduction in labor cost was applied on electrical installations, such as those for CP, based on the number of installations (Means 1990). The adjustment factors are shown in Table I.9

Distribution of Material

In bridge repair projects, when the bridge spans over water, the materials might be stored at shore, and workers might need to go back and forth to distribute the material. Table I.10 lists labor productivity factors based on the distance from the element being repaired to the stock pile. Such productivity factors were provided by Mechanical City.

Table I.8 Productivity Factors Based on Pile Cap Height

Pile Cap Height Range	Productivity Factor
Less than 15 ft.	1.00
15 ft. to 20 ft.	1.10
20 ft. to 25 ft.	1.20
25 ft. to 30 ft.	1.30
30 ft. to 35 ft.	1.40
35 ft. to 40 ft.	1.50
Over 40 ft.	1.60

(Used by Permission of RS Means Company, Inc., Table was Modified)[1]

Table I.9 Economy of Scale Adjustment Factors

Number of Wiring Devices Range	Productivity Factor
Less than 10 each	1.00
10 to 25 each	1.20
25 to 50 each	1.25
50 to 100 each	1.30
Over 100 each	1.35

(Used by Permission of RS Means Company, Inc., Table was Modified)[1]

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(1) From Means Estimating Handbook, 1990.

Table I.10 Distribution of Material Adjustment Factors

Distance from Stockpile	Productivity Factor
Less than 300 ft.	1.00
300 ft. to 499 ft.	1.03
500 ft. to 999 ft.	1.04
1000 ft. or more	1.06

(Data provided by Ted Gibson, Fax, April 28, 1999)

Miscellaneous Productivity Factors

Additional productivity factors used in the model were applied if (1) the bridge was located in a congested area, (2) work was performed at night, (3) overtime above 50 hours was required. Mechanical City provided a range of values for such productivity factors, which are listed in Table I.11.

Table I.11 Miscellaneous Productivity Factors

Description	Productivity Factor Range
Congested area	1.00
Night work	1.03
Overtime work above 50 hrs.	1.04

(Data provided by Ted Gibson, Fax, April 28, 1999)

APPENDIX J

NAVY DIVER SAMPLE SURVEY

PRODUCTIVITY QUESTIONNAIRE

Several questions in this questionnaire refer to the term “productivity”. By “productivity” we mean how fast you perform a construction task. As an example, let us assume, that under normal conditions, you can perform a construction task in a given amount of time. However, under certain circumstances you can only perform ¾ of the construction task in the same amount of time. In such a case, your productivity is only .75 (= ¾) or 75%, if expressed as a percentage. 100% Productivity corresponds to optimum conditions encountered underwater, when neither the current speed, temperature, visibility, nor pressure delays your work.

Please, indicate the range that best describes the number of years you have worked as a construction diver.

_______ Less than 1 year
_______ More than 1 year but less than 5 years
_______ More than 5 years but less than 10 years
_______ More than 10 years but less than 15 years
_______ More than 15 years but less than 20 years
_______ More than 20 years

For each one of the construction tasks listed below, please, based on your experience, indicate the approximate average time it will take you to complete the task, assuming that you are working under optimum conditions, and your productivity is 100%. All activities referred to concrete piles.

Activity	Unit	Average Duration	Minimum Duration	Maximum Duration
Sound test concrete area	$Foot^2$			
Remove large pieces of unsound concrete	$Foot^2$ x 1 inch deep			
Remove small pieces of unsound concrete	$Foot^2$ x 1 inch deep			
Clean pile surface	$Foot^2$			
Apply a concrete patch on pile surface	$Foot^2$			
Saw cut concrete	Foot			
Clean reinforcement	Foot			
Place steel mesh on a pile	Each			
Weld steel mesh on a pile	Each			
Place additional rebar on a pile	Each			
Weld additional rebar to existing reinforcement	Each			
Place rebar cage around pile	Each			
Place additional stirrup on a pile	Each			
Install lateral formwork (to hold pile jacket in place)	Each			
Install bottom formwork (pile jacket)	Each			
Place braces around jacket	Each			
Excavate sand below mudline (jacket foundation)	$Foot^3$			

Activity	Unit	Average Duration	Minimum Duration	Maximum Duration
Excavate coarse soil (jacket foundation)	$Foot^3$			
Excavate clay below mudline (jacket foundation)	$Foot^3$			
Fill foundation excavation with same material	$Foot^3$			
Fill foundation excavation with grout	$Foot^3$			
Apply epoxy to jacket seams	Foot			
Insert fasteners along jacket seam	Each			
Place jacket around the pile	Each			
Cast grout inside jacket (from the top)	$Foot^3$			
Cast grout inside jacket (injection ports)	$Foot^3$			
Cast jacket bottom seal	$Foot^3$			
Seal leaks (while casting grout)	Each			
Place or remove grout hose inside jacket from top	Each			
Attach or remove grout hose from injection ports	Each			
Remove bottom formwork (pile encapsulation)	Each			
Remove lateral formwork (pile encapsulation)	Each			
Remove lateral braces	Each			

Please, for each of the cases listed below, indicate if the range of values that we have selected to define low, medium, high and extremely high currents are reasonable to you.

LOW CURRENT [less or equal to 1 knot] Yes _______ No _______
MEDIUM CURRENT[greater than 1 knot but less or equal to 1.5 knots] Yes _______ No _______
HIGH CURRENT [greater than 1.5 knots but less or equal to 2.5 knots Yes _______ No _______
EXTREMELY HIGH CURRENT [greater than 2.5 knots] Yes _______ No _______

If your answer was "No" in any of the cases in question 3, please recommend below a better range.

LOW CURRENT [less or equal to _______ knot]
MEDIUM CURRENT [greater than _______ knot but less or equal to _______ knots]
HIGH CURRENT [greater than _______ knots but less or equal to _______ knots]
EXTREMELY HIGH CURRENT [greater than _______ knots]

Have you perceived a reduction in productivity due to current speed?

Yes ______
No ______

Please, provide a percentage which best describes your average, maximum and minimum productivity while repairing concrete piles, for each one of the water current speed ranges defined below.

	PRODUCTIVITY Average	Maximum	Minimum
LOW CURRENT [less or equal to 1 knot]	_____ %	_____ %	_____ %
MEDIUM CURRENT[greater than 1 knot but less or equal to 1.5 knots]	_____ %	_____ %	_____ %
HIGH CURRENT [greater than 1.5 knots but less or equal to 2.5 knots]	_____%	_____%	_____%
EXTREMELY HIGH CURRENT [greater than 2.5 knots]	_____%	_____%	_____%

For each one of the cases listed below, please, indicate if the range of values that we have selected to define good, medium and poor visibility are reasonable to you.

GOOD VISIBILITY [greater than 3 feet] Yes ______ No ______
MEDIUM VISIBILITY [greater than 1 foot but less or equal to 3 feet] Yes ______ No ______
POOR VISIBILITY [less or equal to 1 foot] Yes ______ No ______

If your answer was "No" in any of the cases in question 7, please recommend below a better range.

GOOD VISIBILITY [greater than ______ feet]
MEDIUM VISIBILITY[greater than ______ feet but less or equal to ______ feet]
POOR VISIBILITY [less or equal to ______ feet]

Have you perceived a reduction in productivity due to visibility?

Yes ______
No ______

Please, provide a percentage which best describes your average, maximum and minimum productivity while repairing concrete piles, for each one of the visibility ranges defined below.

	PRODUCTIVITY		
	Average	Maximum	Minimum
GOOD VISIBILITY [greater than 3 feet]	____ %	____ %	____ %
MEDIUM VISIBILITY [greater than 1 foot but less or equal to 3 feet]	____%	____%	____%
POOR VISIBILITY [less or equal to 1 foot]	____%	____%	____%

For each one of the cases listed below, please indicate if the range of values that we have selected to define hot, moderate, cold and very cold water temperature are reasonable to you.

HOT WATER [greater or equal to 80 °F] ____ Yes ____ No
MODERATE WATER [less than 80 °F but greater or equal to 65 °F] ____Yes ____ No
COLD WATER [less than 65 °F but greater or equal to 40 °F] ____Yes ____ No
VERY COLD WATER [less than 40 °F] ____Yes ____ No

If your answer was "No" in any of the cases in question 11, please recommend below a better range.

HOT WATER [greater or equal to ____°F)]
MODERATE WATER [less than ____ °F but greater or equal to ____°F]
COLD WATER [less than ____ °F but greater or equal to ____ °F]
VERY COLD WATER [less than ____ °F

The Navy Diving Manual provides guidelines to determine the amount of time a diver can stay below the water surface based on water temperature/gear. Let one assume that for a given construction task required during the repair of a concrete pile, you do not need to go to the surface because of temperature/gear limitations. In such a case, have you perceived a reduction in productivity due to water temperature only?

Yes ______
No ______

Considering the same assumptions stated in Question 13, please, provide a percentage which best describes your average, maximum and minimum productivity while repairing concrete piles, for each one of the water temperatures ranges defined below.

	PRODUCTIVITY		
	Average	Maximum	Minimum
HOT WATER [greater or equal to 80 °F]	____ %	____ %	____ %
MODERATE WATER [less than 80 °F but greater or equal to 65 °F]	____ %	____ %	____ %
COLD WATER [less than 65 °F but greater or equal to 40 °F]	____ %	____ %	____ %
VERY COLD WATER [less than 40 °F]	____ %	____ %	____ %

For each one of the cases listed below, please indicate if the range of values that we have selected to define low, moderate, high and very high pressure, based on depth, are reasonable to you.

LOW PRESSURE [less or equal to 60 fsw]	Yes ____	No ____
MODERATE PRESSURE [less or equal to 130 fsw but greater than 60 fsw]	Yes ____	No ____
HIGH PRESSURE [less or equal to 190 fsw but greater than 130 fsw]	Yes ____	No ____
VERY HIGH PRESSURE [less or equal to 285 fsw but greater than 190 fsw]	Yes ____	No ____

If your answer was "No" in any of the cases in question 15, please recommend a better range below.

LOW PRESSURE [less or equal to ____ fsw]
MODERATE PRESSURE [less or equal to ____ fsw but greater than ____ fsw]
HIGH PRESSURE [less or equal to ____ fsw but greater than ____ fsw]
VERY HIGH PRESSURE [less or equal to ____ fsw but greater than ____ fsw]

The Navy Diving Manual provides guidelines to determine the amount of time a diver can stay below water based on water depth/ pressure. The water depth/pressure also defines decompression times. Let us assume that for a given construction task required during the repair of a concrete pile, you do not need to go to the surface because of pressure limitations. Let us also ignore the time you spent decompressing when analyzing the time it takes you to complete a construction task. In such a case, have you perceived a reduction in productivity due to pressure only?

Yes ______
No ______

Considering the same assumptions stated in Question 17, please, provide a percentage which best describes your average, maximum and minimum productivity while repairing concrete piles, for each of the water temperatures ranges defined below.

	PRODUCTIVITY		
	Average	Maximum	Minimum
LOW PRESSURE [less or equal to 60 fsw]	____ %	____ %	____ %
MODERATE PRESSURE [less or equal to 130 fsw but greater than 60 fsw]	____ %	____ %	____ %
HIGH PRESSURE [less or equal to 190 fsw but greater than 130 fsw]	____ %	____ %	____ %
VERY HIGH PRESSURE [less or equal to 285 fsw but greater than 190 fsw]	____ %	____ %	____ %

Did we miss something? Please, provide any comment that may help us to improve this questionnaire or to better understand underwater construction productivity.

We would like to thank you for the time you dedicated to answer this questionnaire. Your opinions are valuable to us. Please, return this questionnaire to the following address, no later than January 6, 2001:

Patricia Thaesler
15206 Alexis Drive
Tampa, FL 33624

APPENDIX K

CONSTRUCTION DATA FROM MELBOURNE FIELD TRIPS

The construction data, presented in this Appendix were observed daily during a two-month period, in Melbourne, Florida. According to the design engineer, this project was typical and represented the majority of projects involving the installation of titanium impressed current CP jackets (Firlotte 1999). The project specifications were based on current specifications used by the FDOT and quality control guidelines recommended by Corrpro, a leading corrosion engineering firm, which supervised the installation of a large number of integral pile jackets throughout the country.

K.1 Project Description

The construction project required the installation of an integral CP pile jacket system on bridge pilings in Melbourne, Florida. The bridge was located on State Route 404 over the Indian River Relief, in Brevard County. Installation of thirty-six CP jackets started in July 1999 and ended in November 1999. The repair was done under FDOT State Project 70004-3502.

K.2 Work Breakdown

The construction process observed during this project consisted of the following tasks: continuity testing, continuity bonding, negative connection installation, reference cell installation, concrete and reinforcement repair, formwork and jacket placement, grout placement and electrical installation.

K.2.1 Continuity Testing

The first step in the installation of a CP jacket was to insure that all the strands within the concrete columns were electrically continuous.

In the case of mild longitudinal reinforcement, the transverse shear reinforcement is tied to the longitudinal reinforcement, and this fact insures electrical continuity within the reinforcement. In the case of prestressing strands, the shear reinforcement is placed around the strands and it is often not tied to them, so that some strands may not touch the shear reinforcement, which results in electrically discontinuous strands.

A prestressing strand and the transverse reinforcement are shown in Figure K.1. According to guidelines established by FDOT, continuity testing was conducted no later than 96 hours after exposing the strands. The time limit was set to prevent corrosion of reinforcement that has been exposed for testing. Each strand was tested. The holes used for continuity testing were rinsed with fresh water and sealed with a latex modified mortar. The procedure used to test the strands is explained below.

Figure K.1 Separation Between Strands and Transverse Reinforcement

Locate the strands

The contractor used the design bridge plans to determine the position of the strands.

Expose the strands

Strands were exposed by drilling or coring. According to FDOT specifications, the holes were alternated at a minimum distance of one ft, with 0.5 inches tolerance vertically between adjacent bars as shown in Figure K.2 (a) and (b) (FDOT TSP 70004-3502, pg. 8). There was a hole per strand. The holes were located at least one ft. above maximum high tide (MHT) to prevent contact with seawater, but they were below the top of the jacket. The engineer recommended carefully drilling a ½ in. diameter hole (FDOT QCP 70004-3502, pg. 4). The maximum accepted diameter was ¾ in. (FDOT TSP 70004-3502, pg. 8). According to observations in the field, ½ in. diameter holes did not expose enough steel to measure continuity. Holes that were 5/8 in. diameter exposed a larger area of strand, which facilitated the testing. Due to inherent limitations associated with drilling a hole without seeing the exact location of the steel, damage to the steel occurred. This fact is illustrated in Figure K.3, which shows strands with a partial loss of cross section that was removed from the strand during drilling. In some instances, it was necessary to drill the hole again to expose a larger area of steel because the hole drilled originally did not expose the steel strand. Also, in some cases, the real strand location might vary from the as-built plans, thus making it necessary to drill a new hole. In such cases, the new hole was drilled close to the existing one.

Rinse holes

It was useful to rinse the holes with fresh water after drilling to clean the area of exposed strands. A worker rinsing the hole with fresh water is shown in Figure K.4.

Select the ground location

The ground location was the area of strand exposed by one of the holes, which was continuous with at least another strand. Two strands were continuous if the potential difference between them is less than 1.0 mV. Measurement of potential difference is explained in step 5.

Measure the potential difference between strands

To measure the potential difference, it was necessary to connect the negative lead of the voltmeter to the ground terminal and connect the positive lead of the voltmeter to the strand. An ice pick was attached to each lead as shown in Figure K.5 (a). The voltmeter was set to the DC mV scale, and the reading was recorded. If the reading was less than or equal to 1.0 mV, the strand had acceptable continuity. If the reading was greater than 1.0 mV the strand needed continuity bonding (Clem QCP, 70004-3502, pg. 4).

When measuring the potential difference between two strands to determine the ground location, both strands should have acceptable continuity, and one of them could be used as the ground location. If the strands were not continuous (reading was greater than 1.0 mV), another set of two strands was selected until both strands showed acceptable continuity by the method described. After locating two strands with acceptable continuity, one of them was selected as a ground location. The contractor maintained the ice pick in the hole corresponding to the ground location and tested the other strands of the column as shown in Figure K.5 (b).

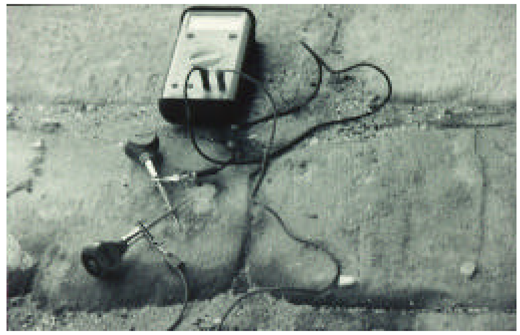
Figures K.2 (a) and (b) Drilling a Concrete Pile to Expose Steel Strands

Figure K.3 Damaged Steel Prestressing Steel Strand

Figure K.4 Rinsing Holes with Freshwater

Measure the potential difference between corroded strands

If there was corroded and exposed strand on the pile, which might (or might not) include loss of cross section, the potential difference measurement was done twice at the same location. One measurement was done between the ground location and the upper section of corroded steel (or above the area that shows loss of section). A second measurement was done between the ground location and the lower section of corroded steel (or below the area that shows loss of section). In this case, it was necessary to drill additional holes since it was not advisable to use the steel that had been exposed by corrosion and deterioration. A concrete pile showing corrosion of steel is shown in Figure K.6.



Figures K.5 (a) and (b) Measurement of Potential Difference Between Strands

Figure K.6 Exposed Steel in a Deteriorated Prestressed Concrete Pile

K.2.2 Continuity Bonding

Continuity bonding was the process used to make all the pretensioned strands and transverse reinforcement electrically continuous. This process was required during the installation of a CP system. In the repair project observed, electrically discontinuous strands were welded to a wire that was also welded to an electrically continuous strand. Electrically continuous strands, as described earlier in the continuity testing section, had a potential difference less than or equal to 1.00 mV with respect to the potential of the "ground location".

As explained earlier, the author observed that the wire used for continuity bonding was welded to the strands. The author recommends an alternative method, such as clamping the wire to the strand, since welding can destroy the strand. The continuity bonding process, which is described in the following paragraphs, represents current engineering practice (FDOT QCP 70004-3502, and FDOT TSP 70004-3502).

The procedure described for continuity bonding was done after completing the continuity testing. This testing identified strands that were electrically discontinuous. Steps one through six that are explained below describe the continuity bonding procedure:

Locate area of concrete to be removed

To perform the continuity bonding, which involved connecting electrically discontinuous strands to an electrically continuous strand, it was necessary to remove concrete from the pile or column to expose the steel strands.

If there were three or more discontinuous strands, then to correct the electrical discontinuity, the contractor cut two grooves around the pile at a distance of three in. The upper groove was located 12 in. below the pile/cap interface as shown in Figure K.7 (FDOT TSP 70004-3502, pg.8). Section AA, shown in Figure K.7, is a section of the pile below the pile cap. In Figure K.8, a pile that had four electrically discontinuous strands is shown. The area of concrete removed was above holes that were drilled to test the strands originally.

If there were two or less electrically discontinuous strands, the contractor was allowed to do a minor continuity correction. Minor continuity correction allowed cutting and removing the steel in the vicinity of the holes drilled to perform the continuity testing to avoid excessive concrete excavation. In this case, a maximum of four in. by four in. excavation within the limits of the jackets were made according to the specifications of the project. This step is shown in detail in Figure K.9. In this figure, the pile has five strands per face. For example, assuming that both strand four and five were electrically discontinuous from the rest of the strands in the front face, and the other strands in that face were continuous, then a wire must be connected to strand three, four and five to establish continuity; and the area to be cut and removed should expose these three strands. By connecting a wire between a discontinuous strand and a continuous strand, the wire permits the flow of current from the continuous strand to the discontinuous strand.

The same treatment applied if strand five and three were electrically discontinuous. A wire was connected between strands five, four and three. If only strand four was electrically discontinuous, then strand four must be connected to strand three rather than strand five because strand three was closer to the center of the column face. The area to be cut and removed exposed these three strands. If strand five was discontinuous, it could be connected either to strand four or strand six.

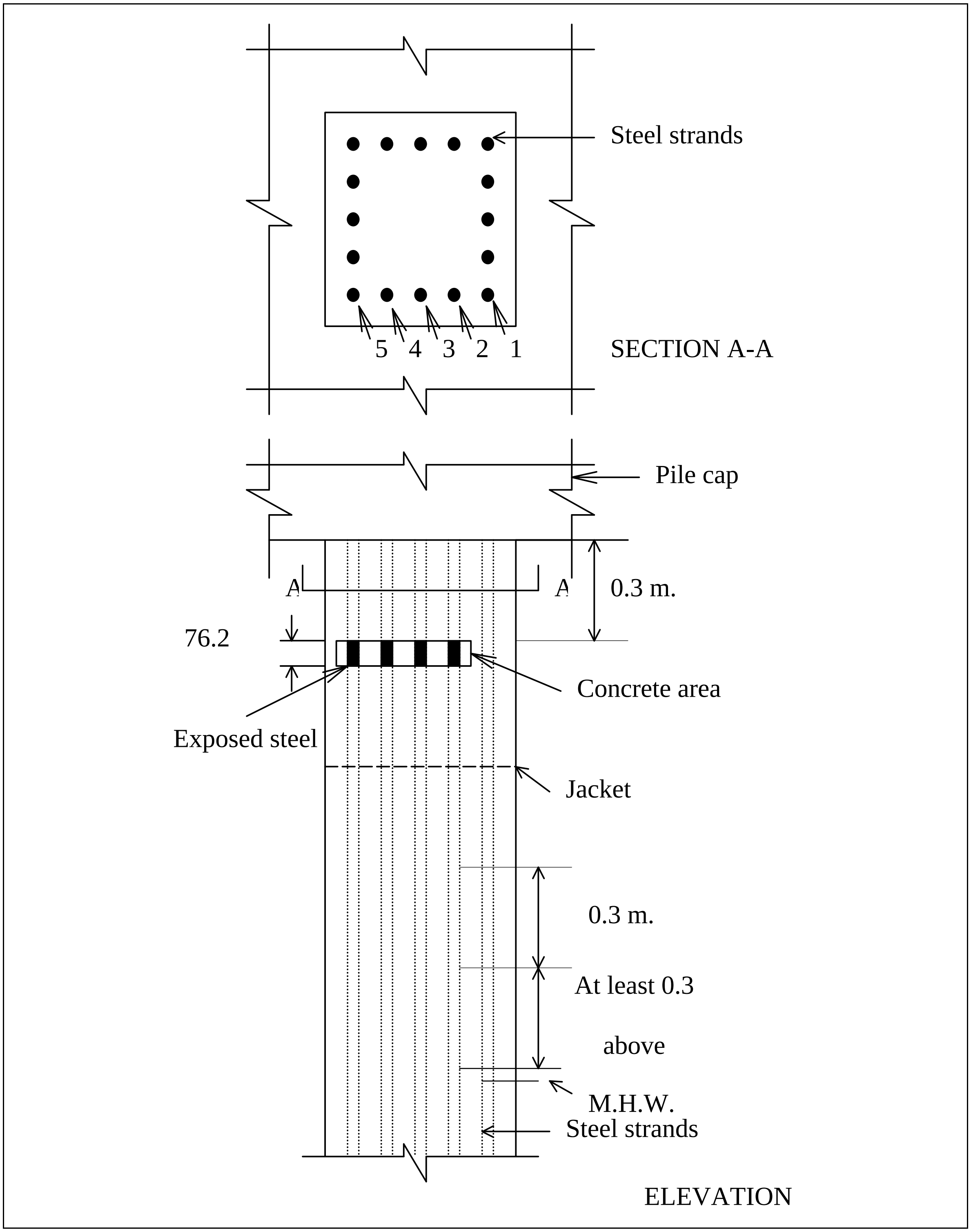


Figure K.7 Area of Concrete to be Removed for Continuity Correction of Three or More Discontinuous Strands

Figure K.8 Pile Showing Exposed Strands to Correct Electrically Discontinuous Strands

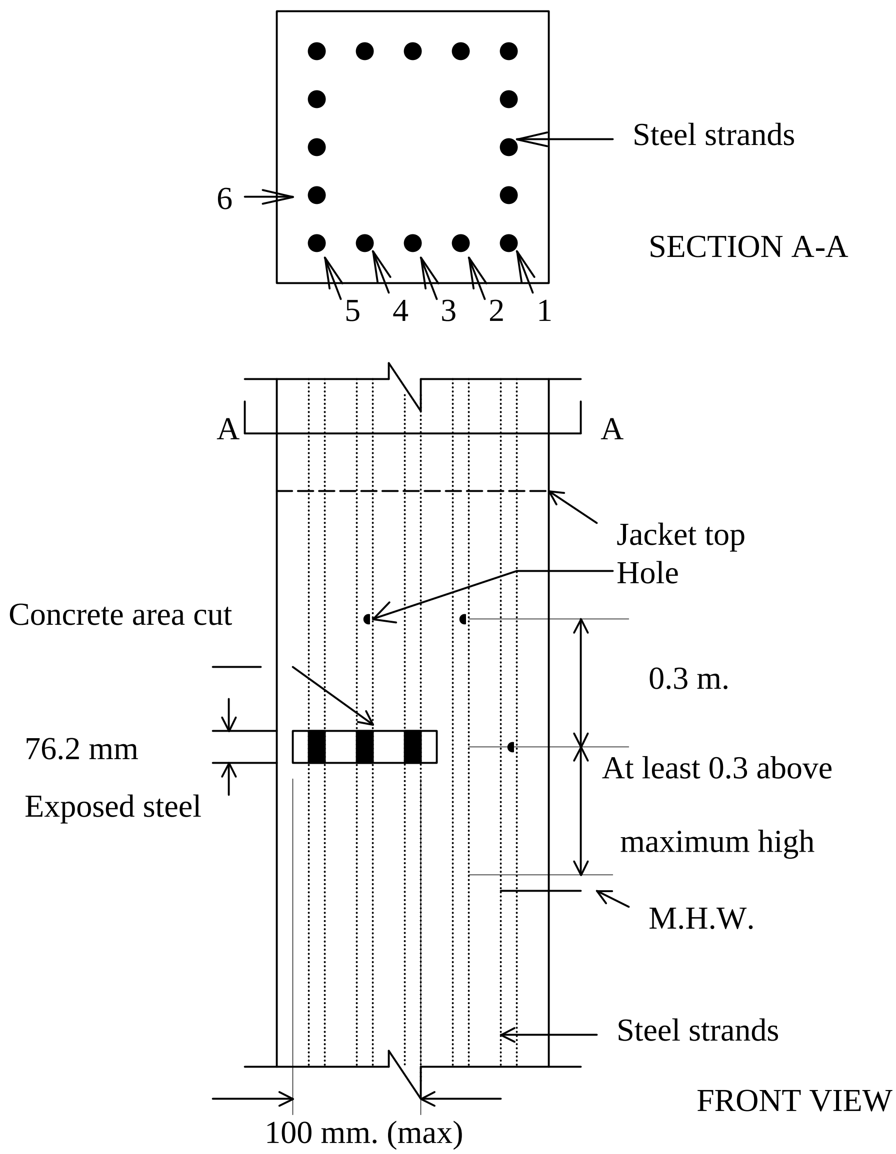


Figure K.9 Area of Concrete to be Removed for Continuity Correction of Two or Less Discontinuous Strands

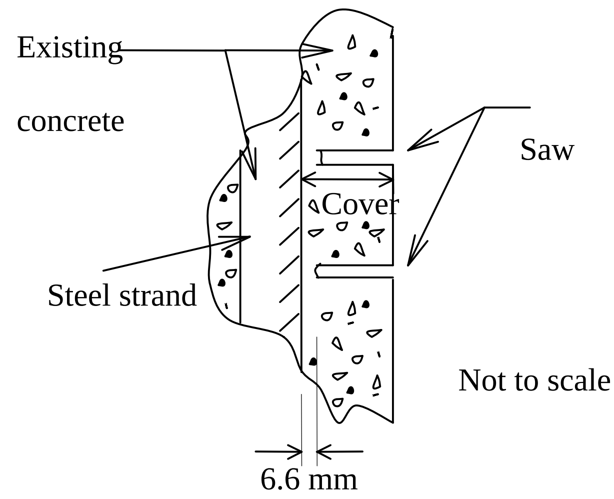


Figure K.10 Proper Cutting of Concrete

Figure K.11 Worker Cutting Grooves on Concrete Pile

Saw cut concrete.

To facilitate removal, concrete was cut to a depth equal to the dimension of the steel cover minus 1/4 in. as shown in Figure K.10 (FDOT Plans of state project 70004-3502, pg. R-5). A worker cutting the concrete, as described previously, is shown in Figure K.11.

Figure K.12 Groove Cut in a Pile to Remove Concrete for Continuity Correction

As shown in Figure K.12, there were two vertical grooves beside the horizontal grooves. This was done to facilitate the removal of concrete in that area. The previous guidelines on properly cutting concrete were followed when cutting the vertical grooves.

Remove concrete

After cutting the concrete properly, the contractor used a 14-pound hammer to remove the concrete contained within the two grooves to expose the steel strands.

Connect wires to strands

After the concrete was removed and the steel strands were exposed, the contractor welded two wires to the exposed strands to provide a redundant path for the continuity connection. There were two wires per connection. Figure K.13 shows a worker welding the wire to the discontinuous strands. The contractor used an oxygen flame at 1200 ^{o}F to weld the continuity connections to the strands. Figure K.14 shows the strand after welding. As shown in Figure K.14, the contractor is measuring the potential difference between the ground and the strands to insure that all strands are electrically continuous after the continuity correction was performed.

Welding as shown in Figure K.13 damages the strand and is therefore not recommended. The technical provisions for the repair project did not specify a welding method to make strands electronically continuous. In the technical special provisions of FDOT project 72291-3514, FDOT specified to use resistance welding to make strands electronically continuous (FDOT TSP 722291-3514, page 11). The Construction Dictionary (1991) described resistance welding as the welding of two pieces held tightly in contact by electrodes through which a heavy alternating current momentarily flows. In the resistance welding process the heat is obtained from resistance of the metal to electric current (www.key-to-steel.com).

Figure K.13 Welding a Wire to the Steel Strands

Figure K.14 Pretensioned Steel Strands after Welding a Wire to the Strands

Install negative connection

The contractor installed an electrical negative connection on each pile receiving CP. The connection was performed by welding a No. 10 copper wire to a spiral tie. The length of the wire was sufficient to reach the junction without any splice (FDOT TSP 70004-3502, pg 7). The junction box was located above the jacket after installing the jacket. The excavation to expose the spiral did not exceed four in. by four in. If the pile required continuity correction, the wire used for the negative connection was welded to a spiral tie that had been exposed to correct electrical discontinuity. The welding of the negative connection was always made within the limits of the jacket elevation according to the project specifications. Figure K.15 shows a copper wire welded to a spiral tie, which was used for the negative connection as shown.

Restore excavations to original profile

All the connections used for continuity correction as well as the negative connection were completely epoxy coated. After the epoxy had sealed, all the excavations were covered with latex modified mortar. Before covering the negative connection and the other connections, the contractor checked that the potential difference between ground and all the strands, as well as between ground and the wire for the negative connection, was less than or equal to 1.00 mV for acceptable continuity as shown in Figure K.16.

The latter shows two leads connected to the terminals of the voltmeter. One lead should touch the ground location, and the other lead should touch the free end of the copper wire used for the negative connection.

Figure K.15 Welding the Copper Wire to the Spiral Tie to Install the Negative Connection

Figure K.16 Checking Continuity between the Steel Strands and the Negative Copper Connection

K.2.3 Negative Connection Installation

The negative connection was a No. 10 copper wire that was welded to the transverse wire reinforcement. The transverse reinforcement was made electrically continuous with the reinforcing bars or presstressed strands. The negative connection was routed to the junction box on each pile.

The negative connection installation was sub-divided into the following sub-tasks:

Excavate concrete to expose spiral tie

The excavation did not exceed four in. by four in. The excavation was performed within the limits of the CP jacket limits. Existing excavations resulting from the continuity bonding procedure were used for this purpose. The existing continuity bonding connection in the excavation that was going to be used for the negative connection was not covered with epoxy until the negative connection was installed. To prevent deterioration of the continuity bonding connection due to delays in epoxy application, the negative connection was installed immediately after the continuity bonding connection, and both connections were covered with epoxy.

Connect negative wire to spiral tie

The negative connection was welded to the transverse shear reinforcement of the concrete column or pile extension. The length of wire used was sufficient to route the wire to a junction box that was going to be located immediately above the jackets without any splices. The location of the junction box was maintained constant at every pile.

Coat negative connection with epoxy

The connection part of the negative wire was coated completely with a non-conductive epoxy so all wires were insulated and protected from corrosion. Prior to coating the connection with epoxy, the contractor hammer tested all connections and verified electrical continuity between the end of the negative wire and the spiral.

Restore excavations to their original profile

The excavations were restored to their original profile by filling them with cement grout.

K.2.4 Reference Cell Installation

The installation of a CP system in a concrete pile required the installation of a reference cell. The reference cell was used to monitor the corrosion of the steel in the concrete pile. Each pile had one silver chloride reference cell. One reference cell before installation is shown in Figure K.17. The following paragraphs describe the procedure to install the reference cell (FDOT QCP 70004-3502).

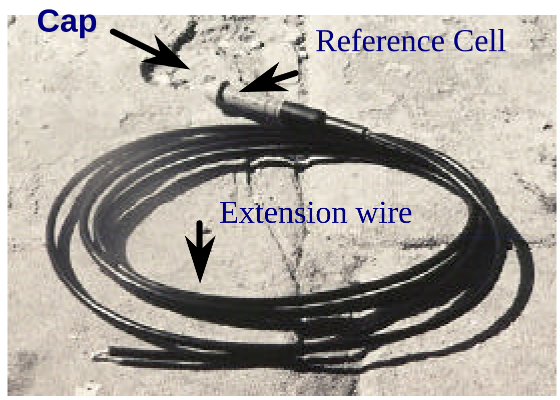


Figure K.17 Reference Cell Before Installation

Make an excavation on the concrete pile

One reference cell was installed on each bent according to the drawings and specifications approximately six in. above the high tide mark. The excavation had not exposed steel in the immediate area. The excavation was circular with a diameter slightly larger than the diameter of the reference cell. The diameter of the reference cell was ¾ inch (FDOT CPMS 70004-3502).

Install reference cell

The cap of the reference cell was removed, and the reference cell was placed in the excavation. Sufficient amount of epoxy was used to adhere the cell to the excavation. Care was taken to avoid applying epoxy to the tip of the reference cell. The length of the extension wire #10 required to reach the junction box was determined, and the excess wire was cut.

Restore excavations to their original profile

The reference cell excavation was patched with latex modified mortar, as shown in Figure K.18.

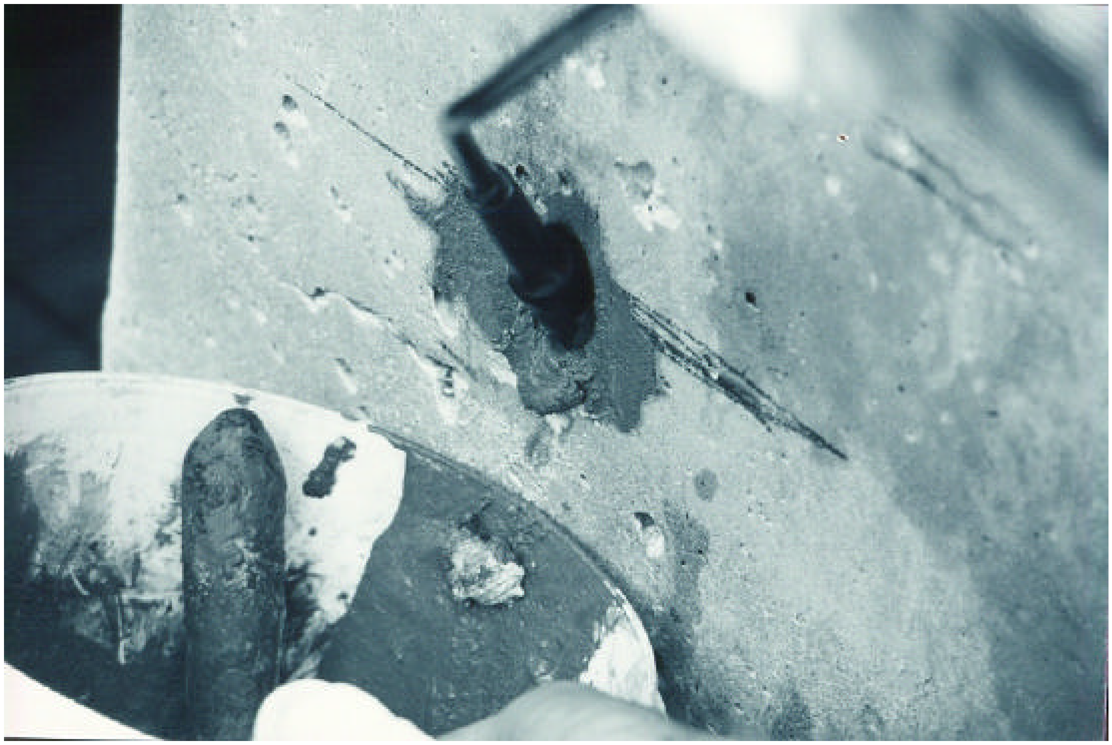


Figure K.18 Installed Reference Cell

K.2.5 Concrete and Reinforcement Repair

Repair of concrete and reinforcement were important parts of the repair. Removal of unsound concrete was fundamental to providing a good bond between the existing pile and the repair materials. In the repair project observed, reinforcement steel on piles was corroded, and the surrounding concrete was cracked and spalled. The contractor sound tested the concrete pile using a light hammer to determine areas that were delaminating. Delaminated areas could be identified by the hollow sound produced by the hammer when impacting the pile. The contractor repaired the concrete and reinforcement as follows:

Place barriers around the pile

Floating turbidity barriers were placed around the piles to prevent the contamination of the waterway with waste materials.

Remove unsound concrete

All cracked or delaminated concrete were removed from the areas that were hollow sounding when tested. Concrete was removed using a 14-pound light duty pneumatic concrete chipper.

Clean exposed steel

All exposed steel was sandblasted to a gray metal, and all debris removed from spalling areas.

Clean pile surface

All debris and marine growth were cleaned from the surface of the concrete pile where the jacket was going to be installed. The method used was sandblasting.

Repair reinforcement

Supplemental reinforcement in the form of a wire mesh was placed around the pile.

K.2.6 Formwork and Jacket Placement

Repairs of bridge piles included placement of a jacket around the pile. The jacket was filled with grout. Formwork held the jacket in place during grout pumping and curing.

Placement of the jacket and formwork consisted of the following steps:

Install the bottom formwork

To support the jacket, a bottom formwork was installed perpendicular to the pile at the elevation equal to mean low tide.

Place the jacket around the pile and adjust stand-offs to maintain the jacket in place

The jacket had a zinc mesh as an integral part. The constructor insured that the zinc mesh was not in contact with any part of the reinforcement.

Fill longitudinal seams with epoxy

The jacket was composed of two parts that snap together through two longitudinal seams. The longitudinal seams were filled with epoxy to improve the bond between the two sections.

Drill polymer fasteners through the seam's length

To prevent failure of the jacket due to opening of the seam length, polymer fasteners were drilled through the jacket seams.

Cover the jacket with plastic wrap

To protect the jacket during grout placement, the contractor covered the jacket with translucent plastic wrap.

Place lateral formwork around the jacket

Lateral formwork was placed around the jacket to provide stability to the jacket. The formwork was kept in place using metal clamps.

Check that the zinc mesh is not in contact with the reinforcement

The contractor measured the potential difference between the jacket mesh and the negative connection to insure that they were not in contact. If the zinc mesh was in contact with the reinforcement, the lateral formwork and the jacket were removed and steps (2) through (7) were repeated.

K.2.7 Grout Casting

The contractor used a two in. diameter hose to pump the grout. The hose was placed at the lower part of the jacket, which was full of water. Pumping of the grout resulted in displacement of the water. Pumping stopped when all the water in the jacket was displaced by the grout. The grout was delivered to the jobsite with a mixing truck. The maximum distance allowed between the truck and the pile was 100 ft. because larger distances resulted in aggregate segregation.

K.2.8 Electrical Installations

The researcher did not observe the installation of the electrical power service station and conduits installations outside the limits of the CP jacket.

K.3 Task Duration

Each construction task was broken down into construction sub-tasks. The time measurements correspond to the construction sub-tasks. FDOT provided bridge drawings that showed plan and elevation of the bridge in which piles, bents and abutments are labeled using the same convention as the one used in Tables K.1 through K.15. However, such bridge drawings are not releasable since 9/11/2001 based on Florida Statute 119.07 (3)(ee). Bridge drawings are on file in FDOT and researcher’s office (FDOT (i)).

Table K.1 Duration of Continuity Testing Construction Tasks

Start	End	Duration (min)	Task Description	Location	Number of Workers	Total Depth of Water
10:35	11:45	70	Measure potential difference	Westbound bent 4 pile A	2	Shore, 1ft deep
11:45	12:31	71	Measure potential difference	Westbound bent 4 pile B	2	Shore, 1 ft deep
12:31	12:48	17	Measure potential difference	Westbound bent 4 pile C	2	Shore, 1 ft deep
10:35	12:48	158	Learn to measure potential difference	Westbound bent 4 pile A, B, C	1	Shore, 1 ft deep
10:35	11:40	65	Re-drill holes to measure potential difference	Westbound bent 4 pile A, B, C, D, E, F	1	Shore, 1 ft deep
11:42	12:30	48	Re-drill holes to measure potential difference	Eastbound bent 4 pile A, B, C, D	1	Shore, 1 ft deep
15:15	15:21	6	Measure potential difference	Eastbound bent 4 pile E	2	Shore, 1ft deep
15:22	15:28	6	Measure potential difference	Eastbound bent 4 pile F	2	Shore, 1ft deep
15:30	15:32	5	Measure potential difference	Eastbound bent 4 pile F	2	Shore, 1ft deep

Table K.2 Duration of Continuity Correction Construction Tasks

Start	End	Duration (min)	Task Description	Location	Number of Workers	Total Depth of Water
11:05	11:29	24	Cut and chip continuity excavation	Westbound bent 2 pile C	1	6 ft deep, near abutment
11:30	11:31	1	Weld continuity wire	Westbound bent 2 pile C	2	6 ft deep, near abutment
11:31	11:32	1	Weld continuity wire	Westbound bent 2 pile C	2	6 ft deep, near abutment
11:32	11:35	3	Measure potential difference	Westbound bent 2 pile C	2	6 ft deep, near abutment
11:35	11:40	5	Move barge to pile A and B	Westbound bent 2 pile A	3	6 ft deep, near abutment
12:15	12:50	35	Cut and chip excavation for neg. connection. Weld negative connection	Westbound bent 2 pile A	1	6 ft deep, near abutment
12:51	12:59	8	Move barge to pile D and E	Westbound bent 2 pile D	3	6 ft deep, near abutment
12:59	13:04	5	Cut and chip continuity excavation	Westbound bent 2 pile D	1	6 ft deep, near abutment
13:08	13:10	4	Weld continuity wire	Westbound bent 2 pile D	2	6 ft deep, near abutment

Table K.2 (Continued)

Start	End	Duration (min)	Task Description	Location	Number of Workers	Total Depth of Water
13:16	13:20	4	Cut continuity excavation	Westbound bent 2 pile D	1	6 ft deep, near abutment
13:20	13:26	6	Cut continuity excavation	Westbound bent 2 pile D	1	6 ft deep, near abutment
13:27	13:32	5	Cut continuity excavation	Westbound bent 2 pile D	1	6 ft deep, near abutment
13:32	13:40	5	Cut continuity excavation	Westbound bent 2 pile E	1	6 ft deep, near abutment
13:36	13:43	8	Chip continuity excavation	Westbound bent 2 pile D	1	6 ft deep, near abutment
13:43	13:44	1	Weld continuity wire	Westbound bent 2 pile D	2	6 ft deep, near abutment
13:44	13:51	7	Chip continuity excavation	Westbound bent 2 pile D	1	6 ft deep, near abutment
13:51	13:57	6	Chip continuity excavation	Westbound bent 2 pile D	1	6 ft deep, near abutment
13:59	14:04	5	Weld continuity wire	Westbound bent 2 pile D	2	6 ft deep, near abutment
13:57	14:04	6	Chip continuity excavation	Westbound bent 2 pile E	1	6 ft deep, near abutment
14:04	14:05	1	Weld continuity wire	Westbound bent 2 pile E	2	6 ft deep, near abutment

Table K.2 (Continued)

Start	End	Duration (min)	Task Description	Location	Number of Workers	Total Depth of Water
14:05	14:07	2	Weld continuity wire	Westbound bent 2 pile D	2	6 ft deep, near abutment
14:07	14:15	8	Weld continuity wire	Westbound bent 2 pile D	2	6 ft deep, near abutment
14:23	14:27	4	Move barge to pile F	Westbound bent 2 pile F	3	6 ft deep, near abutment
14:34	14:37	4	Cut continuity excavation	Westbound bent 2 pile F	1	6 ft deep, near abutment
14:37	14:41	4	Cut continuity excavation	Westbound bent 2 pile F	1	6 ft deep, near abutment
14:41	14:47	6	Cut continuity excavation	Westbound bent 2 pile F	1	6 ft deep, near abutment
14:47	14:54	7	Chip continuity excavation	Westbound bent 2 pile F	1	6 ft deep, near abutment
14:54	14:59	5	Chip continuity excavation	Westbound bent 2 pile F	1	6 ft deep, near abutment
14:59	15:02	3	Chip continuity excavation	Westbound bent 2 pile F	1	6 ft deep, near abutment
14:59	15:56	57	Weld continuity wires in pile F, and install negative connections on piles C, D, E, F	Westbound bent 2 pile C, D, E, F	3	6 ft deep, near abutment

Table K.2 (Continued)

Start	End	Duration (min)	Task Description	Location	Number of Workers	Total Depth of Water
8:40	10:50	90	Cut and chip continuity excavation. Weld continuity wires. Move barge from A to B	Eastbound bent 2 pile A and B	3	6 ft deep, near abutment
10:50	10:55	5	Cut continuity excavation	Eastbound bent 2 pile C	3	6 ft deep, near abutment
10:55	11:00	5	Cut continuity excavation	Eastbound bent 2 pile C	1	6 ft deep, near abutment
11:00	11:07	7	Cut continuity excavation	Eastbound bent 2 pile C	1	6 ft deep, near abutment
11:00	11:08	8	Chip continuity excavation	Eastbound bent 2 pile C	1	6 ft deep, near abutment
11:08	11:16	8	Chip continuity excavation	Eastbound bent 2 pile C	1	6 ft deep, near abutment
11:16	11:27	11	Chip continuity excavation	Eastbound bent 2 pile C	1	6 ft deep, near abutment
11:07	11:15	8	Cut continuity excavation	Eastbound bent 2 pile D	1	6 ft deep, near abutment
11:28	1:00	92	Idle time			

Table K.2 (Continued)

Start	End	Duration (min)	Task Description	Location	Number of Workers	Total Depth of Water
1:00	1:10	10	Chip continuity excavation	Eastbound bent 2 pile D	1	6 ft deep, near abutment
1:10	1:16	6	Chip continuity excavation	Eastbound bent 2 pile D	1	6 ft deep, near abutment
1:20	1:26	6	Weld continuity wire	Eastbound bent 2 pile C	1	6 ft deep, near abutment
1:24	1:29	5	Cut continuity excavation	Eastbound bent 2 pile D	1	6 ft deep, near abutment
1:29	1:35	6	Chip continuity excavation	Eastbound bent 2 pile D	1	6 ft deep, near abutment
1:35	1:57	22	Weld continuity wire Epoxy coat	Eastbound bent 2 pile D	1	6 ft deep, near abutment
2:00	2:08	8	Move barge to pile E and F	Eastbound bent 2 pile E	3	6 ft deep, near abutment
2:14	2:18	4	Cut continuity excavation	Eastbound bent 2 pile F	1	6 ft deep, near abutment
2:18	2:20	2	Cut continuity excavation	Eastbound bent 2 pile F	1	6 ft deep, near abutment
2:20	2:23	3	Cut continuity excavation	Eastbound bent 2 pile F	1	6 ft deep, near abutment
2:23	2:27	4	Cut continuity excavation	Eastbound bent 2 pile F	1	6 ft deep, near abutment

Table K.2 (Continued)

Start	End	Duration (min)	Task Description	Location	Number of Workers	Total Depth of Water
2:18	2:26	8	Chip continuity excavation	Eastbound bent 2 pile F	1	6 ft deep, near abutment
2:26	2:50	24	Chip continuity excavation	Eastbound bent 2 pile F	1	6 ft deep, near abutment
2:50	3:12	22	Weld continuity wire	Eastbound bent 2 pile F	1	6 ft deep, near abutment
2:27	2:50	27	Cut continuity excavation	Eastbound bent 2 pile E	1	6 ft deep, near abutment
2:50	2:57	7	Chip continuity excavation	Eastbound bent 2 pile E	1	6 ft deep, near abutment
2:57	3:04	7	Chip continuity excavation	Eastbound bent 2 pile E	1	6 ft deep, near abutment
3:06	3:13	7	Chip continuity excavation	Eastbound bent 2 pile E	1	6 ft deep, near abutment
9:45	9:50	5	Cut continuity excavation	Westbound bent 4 pile A	3	Shore, 1ft deep
12:42	12:45	3	Install negative connection	Westbound bent 4 pile A	3	Shore, 1ft deep
15:15	15:31	16	Weld continuity wire	Eastbound bent 4 pile B	3	Shore, 1ft deep
15:31	15:33	2	Weld continuity wire	Eastbound bent 4 pile A	3	Shore, 1ft deep
15:34	15:37	3	Install negative connection	Eastbound bent 4 pile A	3	Shore, 1ft deep
15:38	15:41	3	Install negative connection	Eastbound bent 4 pile B	3	Shore, 1ft deep
15:47	15:54	7	Weld continuity wire	Eastbound bent 4 pile C	3	Shore, 1ft deep
15:55	15:59	4	Weld continuity wire	Eastbound bent 4 pile D	3	Shore, 1ft deep
16:03	16:08	5	Weld continuity wire	Eastbound bent 4 pile E	3	Shore, 1ft deep

Table K.3 Duration of Negative Connection Installation Construction Tasks

Start	End	Duration (min)	Task Description	Location	Number of workers	Total Depth of Water
14:59		3	Weld continuity wire	Westbound bent 2 pile F	2	6 ft deep, near abutment
		7	Install negative connection	Westbound bent 2 pile F	2	6 ft deep, near abutment
		6	Move barge to pile D and E	Westbound bent 2 pile D	3	6 ft deep, near abutment
		7	Install negative connection	Westbound bent 2 pile E	2	6 ft deep, near abutment
		7	Install negative connection	Westbound bent 2 pile D	2	6 ft deep, near abutment
		6	Move barge to pile C	Westbound bent 2 pile C	3	6 ft deep, near abutment
		7	Install negative connection	Westbound bent 2 pile C	2	6 ft deep, near abutment
	15:56	14	Idle time. According to field data, productivity for the 2 workers doing the welding was 75 %, so that it assumed that 25% of 57 min was idle time. Field data also corroborate the fact that there were several stops during this working period.			

Table K.3 (Continued)

Start	End	Duration (min)	Task Description	Location	Number of Workers	Total Depth of Water
12:15		5	Cut continuity excavation	Westbound bent 2 pile A	1	6 ft deep, near abutment
		5	Chip continuity excavation	Westbound bent 2 pile A	1	6 ft deep, near abutment
		5	Cut continuity excavation	Westbound bent 2 pile B	1	6 ft deep, near abutment
		5	Chip continuity excavation	Westbound bent 2 pile B	1	6 ft deep, near abutment
		7	Install negative connection	Westbound bent 2 pile A	2	6 ft deep, near abutment
	12:50	7	Install negative connection	Westbound bent 2 pile B	2	6 ft deep, near abutment

Table K.4 Duration of Surface Preparation Construction Tasks

Start	End	Duration (min)	Quantity	Task Description	Location	Number of Workers	Total Depth of Water
9:27	9:29	2	1	Sandblasting	Westbound bent 4 pile F	2	Shore, 1ft deep
9:30	9:32	2	1	Sandblasting	Westbound bent 4 pile E	2	Shore, 1ft deep
10:41	10:50	9	1	Sandblasting	Westbound bent 4 pile D	2	Shore, 1ft deep

Table K.5 Duration of Bottom Formwork Installation Construction Tasks

Start	End	Duration (min)	Quantity	Task Description	Location	Number of Workers	Total Depth of Water
7:44	9:06	22	6’x5’x6”	Excavating to install bottom formwork	Eastbound bent 4 pile F	3	Shore, 1ft deep
7:40	9:03	23	6’x5’x6”	Excavating to install bottom formwork	Eastbound bent 4 pile E	3	Shore, 1ft deep
9:05	9:50	45	6’x5’x6”	Excavating to install bottom formwork	Westbound bent 4 pile D	3	Shore, 1ft deep
9:07	11:11	2:02	6’x5’x6”	Excavating to install bottom formwork	Westbound bent 4 pile C	3	Shore, 1ft deep
9:50	11:06	1:16	6’x5’x6”	Excavating to install bottom formwork	Westbound bent 4 pile B	3	Shore, 1ft deep
9:00	11:55	2:55	6’x5’x6”	Excavating to install bottom formwork	Westbound bent 4 pile A	3	Shore, 1ft deep
7:45	8:25	40	6’x5’x6”	Re-excavating and dewatering to install bottom formwork	Westbound bent 4 pile C	3	Shore, 1ft deep
8:56	9:27	31	6’x5’x6”	Re-excavating and dewatering to install bottom formwork	Westbound bent 4 pile E	3	Shore, 1ft deep

Table K.5 (Continued)

Start	End	Duration (min)	Quantity	Task Description	Location	Number of Workers	Total Depth of Water
8:43	9:17	37	1	Install bottom formwork	Eastbound bent 4 pile F	3	Shore, 1ft deep
9:20	9:49	29	1	Install bottom formwork	Eastbound bent 4 pile F	3	Shore, 1ft deep
9:50	10:17	27	1	Install bottom formwork	Eastbound bent 4 pile D	3	Shore, 1ft deep
11:10	11:55	45	1	Install bottom formwork	Westbound bent 4 pile F	3	Shore, 1ft deep
11:11	11:35	24	1	Install bottom formwork	Eastbound bent 4 pile D	3	Shore, 1ft deep
11:35	12:00	35	1	Install bottom formwork	Eastbound bent 4 pile C	3	Shore, 1ft deep
11:55	12:34	39	1	Install bottom formwork	Westbound bent 4 pile A	3	Shore, 1ft deep
12:00	12:34	34	1	Install bottom formwork	Eastbound bent 4 pile B	3	Shore, 1ft deep
12:34	14:03	2:28	1	Install bottom formwork	Eastbound bent 4 pile A	3	Shore, 1ft deep
13:00	13:47			Install bottom formwork	Westbound bent 4 pile B	3	Shore, 1ft deep
9:46	10:15	29	1	Re-install bottom formwork	Westbound bent 4 pile F	3	Shore, 1ft deep
10:16	10:40	24	1	Install bottom formwork	Westbound bent 4 pile C	3	Shore, 1ft deep

Table K.6 Duration of Jacket Placement Construction Tasks

Start	End	Duration (min)	Quantity	Task Description	Location	Number of Workers	Total Depth of Water
9:42	9:44	2	1	Place jacket around pile	Westbound bent 4 pile F	3	Shore, 1ft deep
9:45	9:49	4	1	Drill fasteners along jacket seam	Westbound bent 4 pile F	3	Shore, 1ft deep
9:50	9:52	2	1	Place jacket around pile	Westbound bent 4 pile E	3	Shore, 1ft deep
9:52	9:58	6	1	Drill fasteners along jacket seam	Westbound bent 4 pile E	3	Shore, 1ft deep
9:59	10:02	3	1	Wrap jacket with plastic	Westbound bent 4 pile E	3	Shore, 1ft deep
10:03	10:06	3	1	Place formwork	Westbound bent 4 pile E	3	Shore, 1ft deep
10:07	10:13	6	1	Place claps to hold formwork	Westbound bent 4 pile E	3	Shore, 1ft deep
10:13	10:15	2	1	Place formwork	Westbound bent 4 pile F	3	Shore, 1ft deep
10:16	10:24	2	1	Place claps to hold formwork	Westbound bent 4 pile F	3	Shore, 1ft deep
10:51	10:54	3	1	Place jacket around the pile	Westbound bent 4 pile D	3	Shore, 1ft deep

Table K.6 (Continued)

Start	End	Duration (min)	Quantity	Task Description	Location	Number of Workers	Total Depth of Water
10:55	11:01	6	1	Drill fasteners along jacket seam	Westbound bent 4 pile D	3	Shore, 1ft deep
11:01	11:04	3	1	Place jacket around the pile	Westbound bent 4 pile C	3	Shore, 1ft deep
11:05	11:11	6	1	Drill fasteners along jacket seam	Westbound bent 4 pile C	3	Shore, 1ft deep
12:47	12:50	3	1	Place jacket around the pile	Westbound bent 4 pile A	3	Shore, 1ft deep
12:51	12:58	7	1	Drill fasteners along jacket seam	Westbound bent 4 pile A	3	Shore, 1ft deep
14:40	14:47	7	1	Place jacket around pile	Westbound bent 2 pile C	3	2 ft deep, near abutment
14:49	14:52	3	1	Drill fasteners along jacket seam	Westbound bent 2 pile C	3	2 ft deep, near abutment
14:56	15:02	6	1	Wrap jacket with plastic	Westbound bent 2 pile C	3	0-3 inch deep, near abutment
14:56	15:02	6	1	Place formwork	Westbound bent 4 pile E	3	0-3 inch deep, near abutment
15:04	15:20	16	1	Place claps to hold formwork	Westbound bent 4 pile E	3	0-3 inch deep, near abutment

Table K.6 (Continued)

Start	End	Duration (min)	Quantity	Task description	Location	Number of Workers	Total Depth of Water
8:00	11:30	3:30	7	Install bottom form work	Eastbound bent 2 pile A, B, C, D, E, F	3	6 ft deep, near abutment
12:01	12:03	2:00	1	Sandblast	Westbound bent 2 pile C	2	6 ft deep, near abutment
12:05	12:54	49	2	Grouting	Westbound bent 2 pile C	3	6 ft deep, near abutment
1:11	1:28	17		Loading formwork	Westbound bent 2 pile C	2	6 ft deep, near abutment
2:40	2:47	7	1	Placing Jacket	Westbound bent 2 pile C	2	6 ft deep, near abutment

Table K.7 Duration of Grout Casting Construction Tasks

Start	End	Duration (min)	Quantity	Task Description	Location	Number of Workers	Total Depth of Water
8:10	8:53	43	1	Place barriers around pile	Westbound bent 2, pile A, B, C, D, E, F	3	6 ft deep, near abutment
10:24	10:47	10	1	Place concrete hose	Westbound bent 2 pile C	5	6 ft deep, near abutment
10:47	10:49	2	1	Pump grout	Westbound bent 2 pile C	3	6 ft deep, near abutment
10:50	10:52	3	1	Pump grout	Westbound bent 2 pile D	3	6 ft deep, near abutment
10:53	10:55	2	1	Pump grout	Westbound bent 2 pile E	3	6 ft deep, near abutment
10:55	10:57	2	1	Pump grout	Westbound bent 2 pile F	3	6 ft deep, near abutment
10:58	11:00	2	1	Pump grout	Eastbound bent 2 pile A	3	6 ft deep, near abutment
11:01	11:03	2	1	Pump grout	Eastbound bent 2 pile B	3	6 ft deep, near abutment
11:04	11:06	2	1	Pump grout	Eastbound bent 2 pile C	3	6 ft deep, near abutment
11:06	11:10	4	1	Pump grout	Eastbound bent 2 pile D	3	6 ft deep, near abutment
11:10	11:12	2	1	Pump grout	Eastbound bent 2 pile E	3	6 ft deep, near abutment
11:13	11:15	2	1	Pump grout	Eastbound bent 2 pile F	3	6 ft deep, near abutment

Table K.8 Duration of Formwork Removal Construction Tasks

Start	End	Duration (min)	Quantity	Task Description	Location	Number of Workers	Total Depth of Water
7:45	7:53	8	1	Removing bottom formwork	Westbound bent 2 pile A	1	2 ft deep, near abutment
7:54	8:03	7	1	Removing bottom formwork	Westbound bent 2 pile B	1	2 ft deep, near abutment
8:15	8:19	4	1	Removing bottom formwork	Westbound bent 2 pile E	1	2 ft deep, near abutment
8:20	8:28	8	1	Removing bottom formwork	Westbound bent 2 pile F	1	2 ft deep, near abutment
12:46	12:52	6	1	Removing bottom formwork	Eastbound bent 2 pile A	1	2 ft deep, near abutment
12:52	12:58	6	1	Removing bottom formwork	Eastbound bent 2 pile B	1	2 ft deep, near abutment
8:15	8:19	4	1	Removing lateral formwork	Eastbound bent 2 pile C	1	2 ft deep, near abutment
8:19	8:23	4	1	Cleaning pile	Eastbound bent 2 pile C	1	2 ft deep, near abutment
8:24	8:32	8	1	Removing lateral formwork	Eastbound bent 2 pile D	1	2 ft deep, near abutment
8:24	8:28	4	1	Cleaning pile	Eastbound bent 2 pile D	1	2 ft deep, near abutment

Table K.8 (Continued)

Start	End	Duration (min)	Quantity	Task Description	Location	Number of Workers	Total Depth of Water
8:40	8:48	8	1	Removing lateral formwork	Eastbound bent 2 pile E	1	2 ft deep, near abutment
8:48	8:56	8	1	Removing lateral formwork	Eastbound bent 2 pile F	1	2 ft deep, near abutment

APPENDIX L

VALIDATION DATA AND RESULTS

Appendix L presents data that were either stored or generated by the Damage Assessment Model, Construction Process Model and Parametric Quantity Model during the validation of the models. The data corresponded to the repair of the Gandy Bridge under FDOT Contract No. 404106-1-52-01.

L.1 <u>Damage Assessment Model Data</u>

The data stored in the Damage Assessment Model were based on detailed bridge inspection data documented in the bridge design drawings provided by Parsons Brinckerhoff Quade & Douglas. Such design drawings are not releasable since 9/11/2001 based on Florida Statute 119.07 (3)(ee). Design drawings are on file in FDOT and researcher's office (FDOT (j)). The inspection data were stored in the sample database using the "damage" Table and are shown in Table L.1. Damage definitions and section definitions were stored in the "sectiondef", "damagedef" and "parameterdef" entities and are shown in Tables L.2 to L.4

Table L.1 Gandy Bridge Inspection Data Stored in the Damage Assessment Model

brkey	***elemkey***	***spankey***	*elemID*	*damageloc*	*damID*	*parameterID*	*i*	*itype*	*value*	unit
100300	226	64	2	SW	5	1	1	default	79	inch
100300	226	64	2	SW	5	2	1	default	12	inch
100300	226	116	4	NE	1	1	1	default	79	inch
100300	226	116	4	NE	1	2	1	default	3	inch
100300	226	116	4	NE	1	3	1	default	12	inch
100300	226	238	7	SW & NW	6	1	4	user	47	inch
100300	226	238	7	SW & NW	6	2	4	user	9	inch
100300	226	238	7	SW & NW	6	3	4	user	20	inch
100300	226	248	6	SW	1	1	1	default	24	inch
100300	226	248	6	SW	1	2	1	default	6	inch
100300	226	248	6	SW	1	3	1	default	12	inch

Table L.2 Definitions of Sections for Prestressed Piles

elemkey	*itype*	*i*	*sectiondef*
226	default	1	Above MLW
226	default	2	Below MLW (0 ft to -3 ft)
226	default	3	Below MLW (-3 ft or more)
226	user	4	Underwater

Table L.3 Sample Values for the Attributes of the "Damagedef" Entity

elemkey	*damID*	*damdef*
226	1	Spall
226	2	Longitudinal reinforcement corrosion
226	3	Crack
226	4	Transverse reinforcement corrosion
226	5	Delamination
226	6	Spall with exposed steel

Table L.4 Sample Values for the Attributes of the "Parameterdef" Entity

elemkey	*damID*	*parameterID*	*parameterdef*
226	1	1	spall length
226	1	2	spall depth
226	1	3	spall width
226	2	1	reinforcement cross section loss
226	2	2	length of reinforcement missing
226	3	1	crack class
226	3	2	crack length
226	4	1	number of stirrups corroded
226	5	1	delamination length
226	5	2	delamination width
226	6	1	spall length
226	6	2	spall depth
226	6	3	spall width

L.2 <u>Construction Process Model Data</u>

L.2.1 Data Used to Create an Estimate

Data used by the Construction Process Model to create an estimate and uniquely identify each element in the estimate were stored in the “estimate” and “estimate_element” tables and are shown in Table L.5 and Table L.6.

Table L.5 Gandy Bridge Data Contained in the “Estimate” Entity

<u>estimateID</u>	*est_date*	*description*
100	6/3/2004	Install integral cathodic protection jackets with sacrificial anode mesh on 4 bridge piles of the Gandy Bridge.

Table L.6 Gandy Bridge Data Contained in the “Estimate_element” Entity

<u>est-elemID</u>	*estimateID*	***brkey***	***elemkey***	***spankey***	*elemID*
101	100	100300	226	64	2
102	100	100300	226	116	4
103	100	100300	226	248	6
104	100	100300	226	238	7

Each pile was uniquely identified using the *<u>est-elemID</u>* attribute. As an example, the identifier for pile 2 on span 64 was 101 (attribute *<u>est-elemID</u>*). Similarly, pile 4 on span 116, pile 6 on span 248 and pile 7 on span 238 were identified as piles 102, 103 and 104 respectively. These latter identifiers were used in the following tables for simplicity and to be consistent with the data stored in the model.

L.2.2 Construction Process Module Flowcharts Input Parameters and Output Results

Pile Access Module

The pile access module flowchart used the following input parameters for the Gandy Bridge:

- Type of access (user input): free.
- Type of environment around the pile (user input): waterway.

Since the type of environment around the pile was a waterway, decision point 2-2 triggered the use of the pile accessibility matrix shown in Figure 5.7. The following additional parameters were required by the pile accessibility matrix:

- Pile grouping based on elements that would be accessed simultaneously
- Water depth
- Damage location

The piles being repaired were located at different spans (span 64, 116, 238 and 248), making it difficult to access the piles simultaneously. Therefore, the author did not group the piles. Visual inspection of the water level conducted by the author at the bridge site indicated that the water depth was definitely greater than five feet, which was the higher bound used in the pile accessibility matrix for the water depth. The damage on the piles located on span 64, 116 and 248 was located above MLW. Damage data could be retrieved from the Damage Assessment Model. For the pile located on span 238, the damage was located underwater, but the inspection report did not provide an exact location of the damage. Being conservative, the author assumed that the location of the damage was greater than three feet, which was the higher bound used in the section definition of bridge pile elements. The output options for the decision points of the pile access module flowchart are shown in Table L.7, and those for the pile accessibility matrix in Table L.8.

Table L.7 Output Options for the Decision Points of the Pile Access Module Flowchart

Decision Point		OUTPUT OPTION			
		Pile			
		101	102	103	104
2-1	Is the working area surrounded by a fence?	NO	NO	NO	NO
2-2	Is the working area surrounded by water?	YES	YES	YES	YES
2-3	Do floating protective barriers need to be placed	YES	YES	YES	YES
2-4	Is the working area surrounded by vehicular traffic?	NA	NA	NA	NA
2-5	Are appropriate traffic control devices on place?	NA	NA	NA	NA
2-6	Does fence need to be replaced?	NO	NO	NO	NO
2-7	Do floating protective barriers need to be removed?	YES	YES	YES	YES
2-8	Do traffic control devices need to be removed?	NO	NO	NO	NO

(NA stands for “Not Applicable”)

Table L.8 Pile Access Defined by the Pile Accessibility Matrix

Pile	Damage Location	Water Depth	Access
101	Above MLW	Greater than 5 feet	Platform
102	Above MLW	Greater than 5 feet	Platform
103	Above MLW	Greater than 5 feet	Platform
104	Below MLW (> 3 feet)	Greater than 5 feet	Platform/scuba diving

Concrete Removal Module

The concrete removal module flowchart used the following input parameters for the Gandy Bridge:

- Type of protection systems already installed on the pile (user input): none.
- Type of repair method (user input): Integral CP jacket with sacrificial anode mesh. This parameter was already selected by the user from a list of options generated from the repair matrices discussed earlier.
- Dimensions of unsound concrete area (Damage Assessment Model): the spall length, width and depth was retrieved from the Damage Assessment Model using the query described in Example 4.2, indicating that there was unsound concrete in the piles.

The output options for the decision points of the concrete removal module flowchart are shown in Table L.9.

Table L.9 Output Options for the Decision Points of the Concrete Removal Module Flowchart

Decision Point		OUTPUT OPTION			
		Pile			
		101	102	103	104
3-1	Is there an existing jacket on the pile?	NO	NO	NO	NO
3-2	Does the repair method include a CP system?	YES	YES	YES	YES
3-3	Is there an existing anode on the pile?	NO	NO	NO	NO
3-4	Is there unsound concrete on the pile?	NA	NA	NA	NA
3-5	Need to dispose of debris?	YES	YES	YES	YES

(NA stands for “Not Applicable”)

Reinforcement Repair Module

The reinforcement repair module flowchart used the following input parameters for the Gandy Bridge:

- Corrosion data (Damage Assessment Model or user input). The model needed to know whether there was corrosion or not. These data were not provided by the detailed inspection report. Thus, the data were not stored in the Damage Assessment Model. The neural networks developed in Chapter VII did not include underwater data or prestressed steel strands, so they could not be applied to the Gandy Bridge. The author assumed that there was no reinforcement corrosion on pile 101, 102 and 103, but there was reinforcement corrosion on pile 104, with more than 25% cross section loss.
- Type of reinforcement in the pile (user input): prestressed steel strands.

- Type of additional/replacement reinforcement (user input): add mild reinforcing steel bar cage.

The output options for the decision points of the reinforcement repair module flowchart are shown in Table L.10.

Table L.10 Output Options for the Decision Points of the Reinforcement Repair Module Flowchart

Decision Point		OUTPUT OPTION			
		Pile			
		101	102	10	104
4-1	Is there reinforcement corrosion?	NO	NO	NO	YES
4-2	Is there considerable cross section loss on reinforcement (25% or more)?	NA	NA	NA	YES
4-3	Provide additional reinforcement?	NA	NA	NA	NO
4-4	Provide additional steel mesh?	NA	NA	NA	YES
4-5	Provide additional rebar (mild steel reinforcing bars)	NA	NA	NA	YES
4-6	Is pile reinforcement prestressed?	NA	NA	NA	NA
4-7	Use a lap weld rebar?	NA	NA	NA	NA
4-8	Provide exterior prestressing?	NA	NA	NA	NA
4-9	Grouted reinforcement?	NA	NA	NA	NA
4-10	Does cathodic protection need to be included?	NA	NA	NA	YES

(NA stands for “Not Applicable”)

Continuity Testing Module Flowchart

There were no decision points in the continuity module flowchart.

Continuity Bonding Module Flowchart

The parameters used by the continuity bonding module flowchart for the Gandy Bridge included:

- Type of reinforcement in the pile (user input): prestressed steel strands
- Probability of having discontinuous strands on any column face (user input): the author used the default values stored in the probability matrix shown in Tables E.4 and E.5.

The parameters required by the continuity bonding module flowchart were empirical probabilities. As discussed in Chapter V, the author did not implement a tool to generate a probabilistic estimate, because it was outside the scope of this research. The same construction process assumed in Chapter V was also assumed for the Gandy Bridge (see Figure 5.11). Based on such an assumption, the output options for the continuity bonding module flowchart are those shown in Table L.11.

Table L.11 Output Options for the Decision Points of the Continuity Bonding Module Flowchart

Decision Point		OUTPUT OPTION			
		Pile			
		101	102	103	104
5-1	Are there any discontinuous strands on any column face?	YES	YES	YES	YES
5-2	Are there three or more discontinuous strands on the column face under consideration?	NO	NO	NO	NO
5-3	Is there an existing excavation for the negative connection?	YES	YES	YES	YES

(NA stands for "Not Applicable")

Reference Cell Installation Module Flowchart

There were no decision points in the continuity testing module flowchart.

Formwork Placement Module Flowchart

The parameters used by the formwork placement module flowchart for the Gandy Bridge were:

- Type of formwork used (user input): bottom and lateral formwork.
- Existing soil elevation (user input): see discussion below.
- Bottom of jacket elevation (user input): see discussion below.

Since the pile was surrounded by water, the user should input the water elevation (MLW). The author did not have existing plans for the Gandy Bridge and was not able to obtain them. Instead, the author visited the Gandy Bridge, and by visually inspecting the water elevation was able to infer that the water was deep enough to insure that the bottom of the jacket was located higher than soil elevation. The author used this assessment to define the output options for the formwork placement module as shown in Table L.12.

Table L.12 Output Options for the Decision Points of the Formwork Placement Module Flowchart

Decision Point		OUTPUT OPTION			
		Pile			
		101	102	10	104
6-1	Does the bottom jacket require bottom formwork?	YES	YES	YES	YES
6-2	Is excavation required to install bottom formwork?	NO	NO	NO	NO
6-3	Is the pile submerged in water?	NE	NE	NE	NE
6-4	Is the water depth 1 foot or more?	NE	NE	NE	NE
6-5	Does the jacket require lateral formwork?	YES	YES	YES	YES

(NE stands for “not executed for the pile under consideration”, see figure 5.13)

Jacket Installation Module Flowchart

The only input parameter used by the jacket placement module for the Gandy Bridge was the type of repair (integral CP jacket with sacrificial anode mesh) and that was already selected because it was required for the module selection flowchart. The output options for the jacket installation module are shown in Table L.13.

Table L.13 Output Options for the Decision Points of the Jacket Installation Module Flowchart

Decision Point		OUTPUT OPTION			
		Pile			
		101	102	103	104
7-1	Does the jacket stay in place?	YES	YES	YES	YES

Grout Casting Module

The only input parameter required by the grout casting modules was the type of repair (integral CP jacket with sacrificial anode mesh). The output options for the grout casting module flowchart are shown in Table L.14.

Table L.14 Output Options for the Decision Points of the Grout Casting Module Flowchart

Decision Point		OUTPUT OPTION			
		Pile			
		101	102	103	104
8-1	Is the equipment required to cast he grout already at the bridge site?	NO	YES	YES	YES
8-2	Does the jacket require a polymer bottom seal?	NO	NO	NO	NO
8-3	Does the jacket have injection ports?	NO	NO	NO	NO
8-4	Does the grout casting equipment need to stay at the bridge site?	YES	YES	YES	YES

Grout Mobilization Module Flowchart

The input parameters required by the grout mobilization flowchart were:

- Type of grout (user input): cement
- Grout mixing location (user input): factory.

In addition, the author assumed that the grout was cast for all the piles using a single grout truck trip to the site, thus all the piles were included in a single "grout casting module" with pile 101 the first one in the group and pile 104 the last in the group. The output options for the grout mobilization module flowchart are shown in Table L.15.

Table L.15 Output Options for the Decision Points of the Grout Mobilization Module Flowchart

Decision Point		OUTPUT OPTION			
		Pile			
		101	102	10	104
9-1	Does the construction task require cement based grout?	YES	NE	NE	NE
9-2	Is the grout mixed at the bridge site?	NO	NE	NE	NE
9-3	Does the jacket have injection ports?	NO	NE	NE	NE

(NE stands for "not executed for the pile under consideration")

Formwork Removal Module Flowchart

The only input parameter required by the formwork removal module was the type of repair (integral CP jacket with sacrificial anode mesh). The output options for the jacket installation module are shown in Table L.16.

Table L.16 Output Options for the Decision Points of the Formwork Removal Module Flowchart

Decision Point		OUTPUT OPTION			
		Pile			
		101	102	10	104
10-1	Does the system require bottom formwork?	YES	YES	YES	YES
10-2	Does the system require lateral formwork?	YES	YES	YES	YES

L.2.3 Construction Tasks Selected for the Gandy Bridge

The data that defined the construction tasks selected by construction module flow-charts for each one of the piles that were repaired on the Gandy Bridge were stored in the in the sample database using the “estimate-task” entity. Such data are shown in Table L.17. The columns that are highlighted in Table L.1 are not part of the “estimate_task” entity but were included because they provided a definition of the construction module flowchart in which the construction task was selected (moduledef) and a definition of the construction subtask (subtaskdef) that was assigned to the element.

Such definitions are stored in the model in the “module” and “subtask”entities. Figures L.1 to L.6 show reports that list the construction tasks required for pile 4 on span 116, pile 7 on span 238 and pile 6 on span 248. The reports were created using the data listed in Table L.17.

Table L.17 Data Stored in the “Estimate_task” Entity for the Gandy Bridge

<u>est-taskID</u>	*est-elemID*	*ModuleID*	*moduledef*	*taskID*	*subtaskID*	*subtaskdef*
600	101	2	PILE ACCESS	PB	1	Place floating protective barriers
601	101	2	PILE ACCESS	PA	5	Access submerged pile using a platform
602	101	3	CONCRETE REMOVAL	CR	3	Sound test concrete area
603	101	3	CONCRETE REMOVAL	CR	4	Remove large pieces of unsound concrete
604	101	3	CONCRETE REMOVAL	CR	5	Remove loose particles and remaining unsound concrete
605	101	3	CONCRETE REMOVAL	CR	6	Dispose of debris
606	101	4	REINFORCEMENT REPAIR	CR	7	Clean pile surface
607	101	11	CONTINUITY TESTING	CT	1	Locate reinforcement position
608	101	11	CONTINUITY TESTING	CT	2	Drill holes on concrete pile to expose reinforcement
609	101	11	CONTINUITY TESTING	CT	3	Select base reinforcement
610	101	11	CONTINUITY TESTING	CT	4	Measure potential difference between base reinforcement and others
611	101	11	CONTINUITY TESTING	CP	1	Patch holes drilled in the concrete pile
612	101	5	CONTINUITY BONDING	CB	1	Locate area of concrete to be removed
613	101	5	CONTINUITY BONDING	CR	8	Saw cut concrete to make a small excavation
614	101	5	CONTINUITY BONDING	CR	9	Remove concrete to make a small excavation
615	101	5	CONTINUITY BONDING	CB	4	Connect continuity wires between existing pile reinforcement
616	101	5	CONTINUITY BONDING	CB	3	Weld negative connection to transverse reinforcement

Table L.17 (Continued)

est-taskID	est-elemID	ModuleID	moduledef	taskID	subtaskID	subtaskdef
617	101	5	CONTINUITY BONDING	CP	2	Cover welds with epoxy
618	101	5	CONTINUITY BONDING	CP	3	Restore small excavations on pile surface to original profile
619	101	12	REFERENCE CELL INSTALLATION	RC	1	Test reference cell
620	101	12	REFERENCE CELL INSTALLATION	RC	2	Locate area of concrete to be removed
621	101	12	REFERENCE CELL INSTALLATION	CR	9	Remove concrete to make a small excavation
622	101	12	REFERENCE CELL INSTALLATION	RC	3	Install reference cell
623	101	12	REFERENCE CELL INSTALLATION	CP	3	Restore small excavations on pile surface to original profile
624	101	6	FORMWORK PLACEMENT	FP	1	Move formwork to working place
625	101	6	FORMWORK PLACEMENT	FP	2	Measure bottom formwork position
626	101	6	FORMWORK PLACEMENT	FP	3	Install bottom formwork
627	101	7	JACKET PLACEMENT	JP	1	Mobilize jackets to bridge site
628	101	7	JACKET PLACEMENT	JP	2	Move jacket to working place
629	101	7	JACKET PLACEMENT	JP	3	Place jacket at proper elevation
630	101	7	JACKET PLACEMENT	JP	4	Apply epoxy to jacket seams
631	101	7	JACKET PLACEMENT	JP	5	Snap jackets together
632	101	7	JACKET PLACEMENT	JP	6	Insert jacket fasteners
633	101	6	FORMWORK PLACEMENT	FP	4	Install lateral formwork

Table L.17 (Continued)

est-taskID	est-elemID	ModuleID	moduledef	taskID	sub-taskID	subtaskdef
634	101	6	FORMWORK PLACEMENT	FP	5	Install lateral braces
635	101	9	GROUT MOBILIZATION	GC	2	Mobilize grout truck to bridge site
636	101	9	GROUT MOBILIZATION	GC	5	Mobilize grout pump to bridge site
637	101	9	GROUT MOBILIZATION	GC	6	Quality control: slump test
638	101	9	GROUT MOBILIZATION	GC	7	Quality control: strength cylinder casting
639	101	9	GROUT MOBILIZATION	GC	12	Place grout hose at the bottom of the jacket
640	101	8	GROUT CASTING	GC	13	Pump grout through a hose
641	101	8	GROUT CASTING	GC	14	Remove grout hose
642	101	8	GROUT CASTING	GC	15	Grout cast in jacket curing time
643	101	8	GROUT CASTING	GC	16	Clean grout waste
644	101	10	FORMWORK REMOVAL	FR	1	Remove bottom formwork
645	101	10	FORMWORK REMOVAL	FR	4	Clean formwork
646	101	10	FORMWORK REMOVAL	FR	2	Remove lateral braces
647	101	10	FORMWORK REMOVAL	FR	5	Clean braces
648	101	10	FORMWORK REMOVAL	FR	3	Remove lateral formwork
649	101	10	FORMWORK REMOVAL	FR	4	Clean formwork
650	101	10	FORMWORK REMOVAL	FR	6	Clean and form grout edges
651	101	2	PILE ACCESS	PB	2	Remove floating protec-tive barriers
700	102	2	PILE ACCESS	PB	1	Place floating protective barriers
701	102	2	PILE ACCESS	PA	5	Access submerged pile using a platform

Table L.17 (Continued)

est-taskID	est-elemID	ModuleID	moduledef	taskID	subtaskID	subtaskdef
702	102	3	CONCRETE REMOVAL	CR	3	Sound test concrete area
703	102	3	CONCRETE REMOVAL	CR	4	Remove large pieces of unsound concrete
704	102	3	CONCRETE REMOVAL	CR	5	Remove loose particles and remaining unsound concrete
705	102	3	CONCRETE REMOVAL	CR	6	Dispose of debris
706	102	4	REINFORCEMENT REPAIR	CR	7	Clean pile surface
707	102	11	CONTINUITY TESTING	CT	1	Locate reinforcement position
709	102	11	CONTINUITY TESTING	CT	2	Drill holes on concrete pile to expose reinforcement
710	102	11	CONTINUITY TESTING	CT	3	Select base reinforcement
711	102	11	CONTINUITY TESTING	CT	4	Measure potential difference between base reinforcement and others
712	102	11	CONTINUITY TESTING	CP	1	Patch holes drilled in the concrete pile
713	102	5	CONTINUITY BONDING	CB	1	Locate area of concrete to be removed
714	102	5	CONTINUITY BONDING	CR	8	Saw cut concrete to make a small excavation
715	102	5	CONTINUITY BONDING	CR	9	Remove concrete to make a small excavation
716	102	5	CONTINUITY BONDING	CB	4	Connect continuity wires between existing pile reinforcement
717	102	5	CONTINUITY BONDING	CB	3	Weld negative connection to transverse reinforcement
718	102	5	CONTINUITY BONDING	CP	2	Cover welds with epoxy

Table L.17 (Continued)

est-taskID	est-elemID	ModuleID	moduledef	taskID	subtaskID	subtaskdef
719	102	5	CONTINUITY BONDING	CP	3	Restore small excavations on pile surface to original profile
720	102	12	REFERENCE CELL INSTALLATION	RC	1	Test reference cell
721	102	12	REFERENCE CELL INSTALLATION	RC	2	Locate area of concrete to be removed
722	102	12	REFERENCE CELL INSTALLATION	CR	9	Remove concrete to make a small excavation
723	102	12	REFERENCE CELL INSTALLATION	RC	3	Install reference cell
724	102	12	REFERENCE CELL INSTALLATION	CP	3	Restore small excavations on pile surface to original profile
725	102	6	FORMWORK PLACEMENT	FP	1	Move formwork to working place
726	102	6	FORMWORK PLACEMENT	FP	2	Measure bottom formwork position
727	102	6	FORMWORK PLACEMENT	FP	3	Install bottom formwork
728	102	7	JACKET PLACEMENT	JP	2	Move jacket to working place
729	102	7	JACKET PLACEMENT	JP	3	Place jacket at proper elevation
730	102	7	JACKET PLACEMENT	JP	4	Apply epoxy to jacket seams
731	102	7	JACKET PLACEMENT	JP	5	Snap jackets together
732	102	7	JACKET PLACEMENT	JP	6	Insert jacket fasteners
733	102	6	FORMWORK PLACEMENT	FP	4	Install lateral formwork
734	102	6	FORMWORK PLACEMENT	FP	5	Install lateral braces
735	102	8	GROUT CASTING	GC	13	Pump grout through a hose
736	102	8	GROUT CASTING	GC	14	Remove grout hose

Table L.17 (Continued)

est-taskID	*est-elemID*	*ModuleID*	*moduledef*	*taskID*	*subtaskID*	*subtaskdef*
737	102	8	GROUT CASTING	GC	15	Grout cast in jacket curing time
738	102	8	GROUT CASTING	GC	16	Clean grout waste
739	102	10	FORMWORK REMOVAL	FR	1	Remove bottom formwork
740	102	10	FORMWORK REMOVAL	FR	4	Clean formwork
741	102	10	FORMWORK REMOVAL	FR	2	Remove lateral braces
742	102	10	FORMWORK REMOVAL	FR	5	Clean braces
743	102	10	FORMWORK REMOVAL	FR	3	Remove lateral formwork
744	102	10	FORMWORK REMOVAL	FR	4	Clean formwork
745	102	10	FORMWORK REMOVAL	FR	6	Clean and form grout edges
746	102	2	PILE ACCESS	PB	2	Remove floating protective barriers
800	103	2	PILE ACCESS	PB	1	Place floating protective barriers
801	103	2	PILE ACCESS	PA	3	Access submerged pile using a platform and scuba diving
802	103	3	CONCRETE REMOVAL	CR	3	Sound test concrete area
803	103	3	CONCRETE REMOVAL	CR	4	Remove large pieces of unsound concrete
804	103	3	CONCRETE REMOVAL	CR	5	Remove loose particles and remaining unsound concrete
805	103	3	CONCRETE REMOVAL	CR	6	Dispose of debris
806	103	4	REINFORCEMENT REPAIR	CR	7	Clean pile surface
807	103	11	CONTINUITY TESTING	CT	1	Locate reinforcement position
808	103	11	CONTINUITY TESTING	CT	2	Drill holes on concrete pile to expose reinforcement
809	103	11	CONTINUITY TESTING	CT	3	Select base reinforcement

Table L.17 (Continued)

est-taskID	*est-elemID*	*ModuleID*	*moduledef*	*taskID*	*subtaskID*	*subtaskdef*
810	103	11	CONTINUITY TESTING	CT	4	Measure potential difference between base reinforcement and others
811	103	11	CONTINUITY TESTING	CP	1	Patch holes drilled in the concrete pile
812	103	5	CONTINUITY BONDING	CB	1	Locate area of concrete to be removed
813	103	5	CONTINUITY BONDING	CR	8	Saw cut concrete to make a small excavation
814	103	5	CONTINUITY BONDING	CR	9	Remove concrete to make a small excavation
815	103	5	CONTINUITY BONDING	CB	4	Connect continuity wires between existing pile reinforcement
816	103	5	CONTINUITY BONDING	CB	3	Weld negative connection to transverse reinforcement
817	103	5	CONTINUITY BONDING	CP	2	Cover welds with epoxy
818	103	5	CONTINUITY BONDING	CP	3	Restore small excavations on pile surface to original profile
819	103	12	REFERENCE CELL INSTALLATION	RC	1	Test reference cell
820	103	12	REFERENCE CELL INSTALLATION	RC	2	Locate area of concrete to be removed
821	103	12	REFERENCE CELL INSTALLATION	CR	9	Remove concrete to make a small excavation
822	103	12	REFERENCE CELL INSTALLATION	RC	3	Install reference cell
823	103	12	REFERENCE CELL INSTALLATION	CP	3	Restore small excavations on pile surface to original profile
824	103	6	FORMWORK PLACEMENT	FP	1	Move formwork to working place
825	103	6	FORMWORK PLACEMENT	FP	2	Measure bottom formwork position

Table L.17 (Continued)

est-taskID	*est-elemID*	*ModuleID*	*moduledef*	*taskID*	*subtaskID*	*subtaskdef*
826	103	6	FORMWORK PLACEMENT	FP	3	Install bottom formwork
827	103	7	JACKET PLACEMENT	JP	2	Move jacket to working place
828	103	7	JACKET PLACEMENT	JP	3	Place jacket at proper elevation
829	103	7	JACKET PLACEMENT	JP	4	Apply epoxy to jacket seams
830	103	7	JACKET PLACEMENT	JP	5	Snap jackets together
831	103	7	JACKET PLACEMENT	JP	6	Insert jacket fasteners
832	103	6	FORMWORK PLACEMENT	FP	4	Install lateral formwork
833	103	6	FORMWORK PLACEMENT	FP	5	Install lateral braces
834	103	8	GROUT CASTING	GC	13	Pump grout through a hose
835	103	8	GROUT CASTING	GC	14	Remove grout hose
836	103	8	GROUT CASTING	GC	15	Grout cast in jacket curing time
837	103	8	GROUT CASTING	GC	16	Clean grout waste
838	103	10	FORMWORK REMOVAL	FR	1	Remove bottom formwork
839	103	10	FORMWORK REMOVAL	FR	4	Clean formwork
840	103	10	FORMWORK REMOVAL	FR	2	Remove lateral braces
841	103	10	FORMWORK REMOVAL	FR	5	Clean braces
842	103	10	FORMWORK REMOVAL	FR	3	Remove lateral formwork
843	103	10	FORMWORK REMOVAL	FR	4	Clean formwork
844	103	10	FORMWORK REMOVAL	FR	6	Clean and form grout edges
845	103	2	PILE ACCESS	PB	2	Remove floating protective barriers
900	104	2	PILE ACCESS	PB	1	Place floating protective barriers

Table L.17 (Continued)

est-taskID	*est-elemID*	*ModuleID*	*moduledef*	*taskID*	*subtaskID*	*subtaskdef*
901	104	2	PILE ACCESS	PA	3	Access submerged pile using a platform and scuba diving
902	104	3	CONCRETE REMOVAL	CR	3	Sound test concrete area
903	104	3	CONCRETE REMOVAL	CR	4	Remove large pieces of unsound concrete
904	104	3	CONCRETE REMOVAL	CR	5	Remove loose particles and remaining unsound concrete
905	104	3	CONCRETE REMOVAL	CR	6	Dispose of debris
906	104	4	REINFORCEMENT REPAIR	RR	1	Clean reinforcement
907	104	4	REINFORCEMENT REPAIR	RR	4	Form rebar cage
908	104	4	REINFORCEMENT REPAIR	RR	5	Place rebar cage around pile
909	104	4	REINFORCEMENT REPAIR	CB	2	Connect continuity wires between existing and new reinforcement
910	104	4	REINFORCEMENT REPAIR	CR	7	Clean pile surface
911	104	11	CONTINUITY TESTING	CT	1	Locate reinforcement position
912	104	11	CONTINUITY TESTING	CT	2	Drill holes on concrete pile to expose reinforcement
913	104	11	CONTINUITY TESTING	CT	3	Select base reinforcement
914	104	11	CONTINUITY TESTING	CT	4	Measure potential difference between base reinforcement and others
915	104	11	CONTINUITY TESTING	CP	1	Patch holes drilled in the concrete pile
916	104	5	CONTINUITY BONDING	CB	1	Locate area of concrete to be removed
917	104	5	CONTINUITY BONDING	CR	8	Saw cut concrete to make a small excavation

Table L.17 (Continued)

est-taskID	est-elemID	ModuleID	moduledef	taskID	subtaskID	subtaskdef
918	104	5	CONTINUITY BONDING	CR	9	Remove concrete to make a small excavation
919	104	5	CONTINUITY BONDING	CB	4	Connect continuity wires between existing pile reinforcement
920	104	5	CONTINUITY BONDING	CB	3	Weld negative connection to transverse reinforcement
921	104	5	CONTINUITY BONDING	CP	2	Cover welds with epoxy
922	104	5	CONTINUITY BONDING	CP	3	Restore small excavations on pile surface to original profile
923	104	12	REFERENCE CELL INSTALLATION	RC	1	Test reference cell
924	104	12	REFERENCE CELL INSTALLATION	RC	2	Locate area of concrete to be removed
925	104	12	REFERENCE CELL INSTALLATION	CR	9	Remove concrete to make a small excavation
926	104	12	REFERENCE CELL INSTALLATION	RC	3	Install reference cell
927	104	12	REFERENCE CELL INSTALLATION	CP	3	Restore small excavations on pile surface to original profile
928	104	6	FORMWORK PLACEMENT	FP	1	Move formwork to working place
929	104	6	FORMWORK PLACEMENT	FP	2	Measure bottom formwork position
930	104	6	FORMWORK PLACEMENT	FP	3	Install bottom formwork
931	104	7	JACKET PLACEMENT	JP	2	Move jacket to working place
932	104	7	JACKET PLACEMENT	JP	3	Place jacket at proper elevation
933	104	7	JACKET PLACEMENT	JP	4	Apply epoxy to jacket seams
934	104	7	JACKET PLACEMENT	JP	5	Snap jackets together

Table L.17 (Continued)

est-taskID	est-elemID	ModuleID	moduledef	taskID	subtaskID	subtaskdef
935	104	7	JACKET PLACEMENT	JP	6	Insert jacket fasteners
936	104	6	FORMWORK PLACEMENT	FP	4	Install lateral formwork
937	104	6	FORMWORK PLACEMENT	FP	5	Install lateral braces
938	104	8	GROUT CASTING	GC	13	Pump grout through a hose
939	104	8	GROUT CASTING	GC	14	Remove grout hose
940	104	8	GROUT CASTING	GC	15	Grout cast in jacket curing time
941	104	8	GROUT CASTING	GC	16	Clean grout waste
942	104	10	FORMWORK REMOVAL	FR	1	Remove bottom form-work
943	104	10	FORMWORK REMOVAL	FR	4	Clean formwork
944	104	10	FORMWORK REMOVAL	FR	2	Remove lateral braces
945	104	10	FORMWORK REMOVAL	FR	5	Clean braces
946	104	10	FORMWORK REMOVAL	FR	3	Remove lateral form-work
947	104	10	FORMWORK REMOVAL	FR	4	Clean formwork
948	104	10	FORMWORK REMOVAL	FR	6	Clean and form grout edges
949	104	2	PILE ACCESS	PB	2	Remove floating protective barriers

CONSTRUCTION TASKS REQUIRED TO REPAIR A SPECIFIC BRIDGE ELEMENT

Estimate Description: Install integral cathodic protection jackets with sacrificial anode mesh on 4 bridge piles of the Gandy Bridge

Bridge No.: 100300

Estimate No.: 100

Estimate Date: 6/3/2004

Bridge Element: Prestressed concrete pile 4 on span 116

Pontis condition State : 2

MODULE	CONSTRUCTION TASK DESCRIPTION
PILE ACCESS	Place floating protective barriers
PILE ACCESS	Access submerged pile using a platform
CONCRETE REMOVAL	Sound test concrete area
CONCRETE REMOVAL	Remove large pieces of unsound concrete
CONCRETE REMOVAL	Remove loose particles and remaining unsound concrete
CONCRETE REMOVAL	Dispose of debris
REINFORCEMENT REPAIR	Clean pile surface
CONTINUITY TESTING	Locate reinforcement position
CONTINUITY TESTING	Drill holes on concrete pile to expose reinforcement
CONTINUITY TESTING	Select base reinforcement
CONTINUITY TESTING	Measure potential difference between base reinforcement and others
CONTINUITY TESTING	Patch holes drilled in the concrete pile
CONTINUITY BONDING	Locate area of concrete to be removed
CONTINUITY BONDING	Saw cut concrete to make a small excavation
CONTINUITY BONDING	Remove concrete to make a small excavation
CONTINUITY BONDING	Connect continuity wires between existing pile reinforcement
CONTINUITY BONDING	Weld negative connection to transverse reinforcement
CONTINUITY BONDING	Cover welds with epoxy
CONTINUITY BONDING	Restore small excavations on pile surface to original profile
REFERENCE CELL INSTALLATION	Test reference cell
REFERENCE CELL INSTALLATION	Locate area of concrete to be removed
REFERENCE CELL INSTALLATION	Remove concrete to make a small excavation

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Figure L.1 Construction Tasks Required to Repair Pile 4 Span 116, Page 1

MODULE	CONSTRUCTION TASK DESCRIPTION
REFERENCE CELL INSTALLATION	Install reference cell
REFERENCE CELL INSTALLATION	Restore small excavations on pile surface to original profile
FORMWORK PLACEMENT	Move formwork to working place
FORMWORK PLACEMENT	Measure bottom formwork position
FORMWORK PLACEMENT	Install bottom formwork
JACKET PLACEMENT	Move jacket to working place
JACKET PLACEMENT	Place jacket at proper elevation
JACKET PLACEMENT	Apply epoxy to jacket seams
JACKET PLACEMENT	Snap jackets together
JACKET PLACEMENT	Insert jacket fasteners
FORMWORK PLACEMENT	Install lateral formwork
FORMWORK PLACEMENT	Install lateral braces
GROUT CASTING	Pump grout through a hose
GROUT CASTING	Remove grout hose
GROUT CASTING	Grout cast in jacket curing time
GROUT CASTING	Clean grout waste
FORMWORK REMOVAL	Remove bottom formwork
FORMWORK REMOVAL	Clean formwork
FORMWORK REMOVAL	Remove lateral braces
FORMWORK REMOVAL	Clean braces
FORMWORK REMOVAL	Remove lateral formwork
FORMWORK REMOVAL	Clean formwork
FORMWORK REMOVAL	Clean and form grout edges
PILE ACCESS	Remove floating protective barriers

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Figure L.2 Construction Tasks Required to Repair Pile 4 Span 116, Page 2

CONSTRUCTION TASKS REQUIRED TO REPAIR A SPECIFIC BRIDGE ELEMENT

Estimate Description:	Install integral cathodic protection jackets with sacrificial anode mesh on 4 bridge piles of the Gandy Bridge
Bridge No.:	100300
Estimate No.:	100
Estimate Date:	6/3/2004
Bridge Element:	Prestressed concrete pile 6 on span 248
Pontis condition State :	2

MODULE	CONSTRUCTION TASK DESCRIPTION
PILE ACCESS	Place floating protective barriers
PILE ACCESS	Access submerged pile using a platform and scuba diving
CONCRETE REMOVAL	Sound test concrete area
CONCRETE REMOVAL	Remove large pieces of unsound concrete
CONCRETE REMOVAL	Remove loose particles and remaining unsound concrete
CONCRETE REMOVAL	Dispose of debris
REINFORCEMENT REPAIR	Clean pile surface
CONTINUITY TESTING	Locate reinforcement position
CONTINUITY TESTING	Drill holes on concrete pile to expose reinforcement
CONTINUITY TESTING	Select base reinforcement
CONTINUITY TESTING	Measure potential difference between base reinforcement and others
CONTINUITY TESTING	Patch holes drilled in the concrete pile
CONTINUITY BONDING	Locate area of concrete to be removed
CONTINUITY BONDING	Saw cut concrete to make a small excavation
CONTINUITY BONDING	Remove concrete to make a small excavation
CONTINUITY BONDING	Connect continuity wires between existing pile reinforcement
CONTINUITY BONDING	Weld negative connection to transverse reinforcement
CONTINUITY BONDING	Cover welds with epoxy
CONTINUITY BONDING	Restore small excavations on pile surface to original profile
REFERENCE CELL INSTALLATION	Test reference cell
REFERENCE CELL INSTALLATION	Locate area of concrete to be removed
REFERENCE CELL INSTALLATION	Remove concrete to make a small excavation

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Figure L.3 Construction Tasks Required to Repair Pile 6 Span 248, Page 1

MODULE	CONSTRUCTION TASK DESCRIPTION
REFERENCE CELL INSTALLATION	Install reference cell
REFERENCE CELL INSTALLATION	Restore small excavations on pile surface to original profile
FORMWORK PLACEMENT	Move formwork to working place
FORMWORK PLACEMENT	Measure bottom formwork position
FORMWORK PLACEMENT	Install bottom formwork
JACKET PLACEMENT	Move jacket to working place
JACKET PLACEMENT	Place jacket at proper elevation
JACKET PLACEMENT	Apply epoxy to jacket seams
JACKET PLACEMENT	Snap jackets together
JACKET PLACEMENT	Insert jacket fasteners
FORMWORK PLACEMENT	Install lateral formwork
FORMWORK PLACEMENT	Install lateral braces
GROUT CASTING	Pump grout through a hose
GROUT CASTING	Remove grout hose
GROUT CASTING	Grout cast in jacket curing time
GROUT CASTING	Clean grout waste
FORMWORK REMOVAL	Remove bottom formwork
FORMWORK REMOVAL	Clean formwork
FORMWORK REMOVAL	Remove lateral braces
FORMWORK REMOVAL	Clean braces
FORMWORK REMOVAL	Remove lateral formwork
FORMWORK REMOVAL	Clean formwork
FORMWORK REMOVAL	Clean and form grout edges
PILE ACCESS	Remove floating protective barriers

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Figure L.4 Construction Tasks Required to Repair Pile 6 Span 248, Page 2

CONSTRUCTION TASKS REQUIRED TO REPAIR A SPECIFIC BRIDGE ELEMENT

Estimate Description:	Install integral cathodic protection jackets with sacrificial anode mesh on 4 bridge piles of the Gandy Bridge
Bridge No.:	100300
Estimate No.:	100
Estimate Date:	6/3/2004
Bridge Element:	Prestressed concrete pile 7 on span 238
Pontis condition State :	3

MODULE	CONSTRUCTION TASK DESCRIPTION
PILE ACCESS	Place floating protective barriers
PILE ACCESS	Access submerged pile using a platform and scuba diving
CONCRETE REMOVAL	Sound test concrete area
CONCRETE REMOVAL	Remove large pieces of unsound concrete
CONCRETE REMOVAL	Remove loose particles and remaining unsound concrete
CONCRETE REMOVAL	Dispose of debris
REINFORCEMENT REPAIR	Clean reinforcement
REINFORCEMENT REPAIR	Form rebar cage
REINFORCEMENT REPAIR	Place rebar cage around pile
REINFORCEMENT REPAIR	Connect continuity wires between existing and new reinforcement
REINFORCEMENT REPAIR	Clean pile surface
CONTINUITY TESTING	Locate reinforcement position
CONTINUITY TESTING	Drill holes on concrete pile to expose reinforcement
CONTINUITY TESTING	Select base reinforcement
CONTINUITY TESTING	Measure potential difference between base reinforcement and others
CONTINUITY TESTING	Patch holes drilled in the concrete pile
CONTINUITY BONDING	Locate area of concrete to be removed
CONTINUITY BONDING	Saw cut concrete to make a small excavation
CONTINUITY BONDING	Remove concrete to make a small excavation
CONTINUITY BONDING	Connect continuity wires between existing pile reinforcement
CONTINUITY BONDING	Weld negative connection to transverse reinforcement
CONTINUITY BONDING	Cover welds with epoxy

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Figure L.5 Construction Tasks Required to Repair Pile 7 Span 238, Page 1

MODULE	CONSTRUCTION TASK DESCRIPTION
CONTINUITY BONDING	Restore small excavations on pile surface to original profile
REFERENCE CELL INSTALLATION	Test reference cell
REFERENCE CELL INSTALLATION	Locate area of concrete to be removed
REFERENCE CELL INSTALLATION	Remove concrete to make a small excavation
REFERENCE CELL INSTALLATION	Install reference cell
REFERENCE CELL INSTALLATION	Restore small excavations on pile surface to original profile
FORMWORK PLACEMENT	Move formwork to working place
FORMWORK PLACEMENT	Measure bottom formwork position
FORMWORK PLACEMENT	Install bottom formwork
JACKET PLACEMENT	Move jacket to working place
JACKET PLACEMENT	Place jacket at proper elevation
JACKET PLACEMENT	Apply epoxy to jacket seams
JACKET PLACEMENT	Snap jackets together
JACKET PLACEMENT	Insert jacket fasteners
FORMWORK PLACEMENT	Install lateral formwork
FORMWORK PLACEMENT	Install lateral braces
GROUT CASTING	Pump grout through a hose
GROUT CASTING	Remove grout hose
GROUT CASTING	Grout cast in jacket curing time
GROUT CASTING	Clean grout waste
FORMWORK REMOVAL	Remove bottom formwork
FORMWORK REMOVAL	Clean formwork
FORMWORK REMOVAL	Remove lateral braces
FORMWORK REMOVAL	Clean braces
FORMWORK REMOVAL	Remove lateral formwork
FORMWORK REMOVAL	Clean formwork
FORMWORK REMOVAL	Clean and form grout edges
PILE ACCESS	Remove floating protective barriers

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Figure L.6 Construction Tasks Required to Repair Pile 7 Span 238, Page 2

L.3 <u>Parametric Quantity Model Data</u>

L.3.1 Input Parameters

Table L.18 Required Parameters Used by the Model to Calculate Jacket Quantities for the Gandy Bridge

Parameter	Parameter Description	Example Pile
$Jacket_{number}$	Number of jackets under consideration.	4 (239)
$Jacket_{total\_umber}$	Total number of jackets in the project	4
$Side_1$	Dimension of the smallest side of the cross section of a rectangular pile being repaired.	20 in.
$Side_2$	Dimension of the largest side of the cross section of a rectangular pile being repaired.	20 in.

Table L.19 Default Values for Secondary Parameters Used by the Model to Calculate Jacket Quantities for the Gandy Bridge

Parameter	Parameter Description	Default Value
CrossID	Pile cross section type	Rectangular
JacketcrossID	Jacket cross section type	Rectangular
t_{clear}	Clearance between the jacket and the original pile	3 in.
$Jacket_{length}$	Jacket length	72 in.
$Jacket_{periphery}$	Periphery of the jacket under consideration	Equation H.1
$Jacket_{area}$	Area of the jacket under consid-eration	Equation H.5
$Transeam_{number}$	Number of transverse seams in the jacket	Equation H.6
$Longseam_{number}$	Number of longitudinal seams in the jacket: If the jacket cross section was rectangular, used 2. If the jacket cross section was circular, used 1	2
$Transeam_{overlap}$	Transverse overlap between two adjacent panels of the jacket	2 in.
$Longseam_{overlap}$	Longitudinal overlap between adjacent panels of the jacket	2 in.

Table L.19 (Continued)

Parameter	Parameter Description	Default Value
$Standoff_{number}$	Number of Standoffs	Equation H.10
$Standoff_{spacing}$	Spacing of standoff pattern along jacket length	18 in.
$Epoxy_{productivity}$	Linear feet of seam that could be sealed with one gallon of epoxy seam (includes waste)	40 (expert knowledge (Snow 1999))
$Longseam_{volume}$	Volume required to seal all longitudinal seams in one jacket	Equation H.11
$Transeam_{volume}$	Volume required to seal all transverse seams in one jacket	Equation H.12
$Fastener_{number}$	Number of fasteners placed along seams to secure them	Equation H.13
$Fastener_{spacing}$	Spacing of fatteners along length of jacket seams	4 in.

L.3.2 Quantity items related to the Jacket Installation Module for the Gandy Bridge

Jacket

Since both the pile and the jacket had a rectangular cross section (crossID= rectangular), (jacketcrossID = rectangular), the jacket periphery was calculated using Equation H.1.

$$\text{jacket}_{\text{periphery}} = 2 \cdot \left(\text{side}_1 + \text{side}_2 + 4 \cdot \text{t}_{\text{clear}}\right) \tag{H.1}$$

$$\text{jacket}_{\text{periphery}} = 2 \cdot \left(20 + 20 + 4 \cdot 2\right) = 96 \text{ in.}$$

$$\begin{aligned}\text{jacket}_{\text{area}} = (&\text{periphery}_{\text{jacket}} + \text{longseam}_{\text{number}} \cdot \text{longseam}_{\text{overlap}} \\ &+ \text{transeam}_{\text{number}} \cdot \text{transeam}_{\text{overlap}}) \cdot \text{jacket}_{\text{length}}\end{aligned} \tag{H.5}$$

$$\text{jacket}_{\text{area}} = (96 + 2 \cdot 2 + 0) \cdot 72 = 7200 \text{ in}^2 = 50 \text{ ft}^2$$

As discussed in Appendix H, the default unit price used in the model for square foot of jacket was provided by expert knowledge \$6.39 for fiberglass (Snow 1999) and \$4.39 for zinc anode mesh (Daily 2004).

$$\text{Jacket cost, fiberglass} = 50 \text{ ft}^2 \cdot 6.39 \frac{\text{dollars}}{\text{ft}^2} = \$319.5$$

$$\text{Jacket cost, anode mesh} = 50 \text{ ft}^2 \cdot 4.39 \frac{\text{dollars}}{\text{ft}^2} = \$219.5$$

The default value for the width of the seam overlap (transverse and longitudinal) was listed in Table L.18, as well as the number of longitudinal seams. A value for the number of transverse seams could be calculated using Equation H.6.

$$15.0 \geq \text{jacket}_{\text{length}} \cdot \text{conversion}_{\text{length}} \qquad \text{transeam}_{\text{number}} = 0 \quad \text{(H.6)}$$

$$15.0 > 72 \cdot \frac{1}{12} = 6\text{; therefore,} \qquad \text{transeam}_{\text{number}} = 0$$

The parameter "$\text{conversion}_{\text{length}}$" converted the jacket length units to feet. The function integer (x) provided the integer part of the number x.

Standoffs

Equations H.10, was used to define the number of standoffs. The standoff pattern was repeated every 18 feet of length of jacket.

$$\text{standoff}_{\text{number}} = 8 \cdot \text{integer}\,\left(\frac{\text{jacket}_{\text{length}}}{\text{standoff}_{\text{spacing}}}\right) \qquad \text{(H.10)}$$

$$\text{standoff}_{\text{number}} = 8 \cdot \text{integer}\,\left(\frac{72}{18}\right) = 32$$

As discussed in Appendix H, the default unit price used in the model for the jacket was provided by expert knowledge as \$0.10 per standoff (Snow 1999).

$$\text{Standoff cost} = 32\ \text{standoffs} \cdot 0.10\ \frac{\text{dollars}}{\text{standoff}} = \$\,3.2$$

Longitudinal Seam Epoxy

The volume of epoxy used to seal the longitudinal seam in the jacket was calculated using Equation H.11.

$$\text{longseam}_{\text{volume}} = \frac{\text{jacket}_{\text{length}} \cdot \text{longseam}_{\text{number}} \cdot \text{conversion}_{\text{length}}}{\text{epoxy}_{\text{productivity}}} \qquad \text{(H.11)}$$

$$\text{longseam}_{\text{volume}} = \frac{72 \cdot 2 \cdot \frac{1}{12}}{40} = 0.3 \text{ gallons}$$

As discussed in Appendix H, the default value used for epoxy productivity was 40 linear ft. of longitudinal seam per gallon of epoxy with average waste. The default unit price used in the model for the seam epoxy was $6.67 per gallon (Snow 1999). Thus the cost of the epoxy volume used to seal the longitudinal seam was calculated above as $2.01.

$$\text{long. seam epoxy cost} = 0.3 \text{ gallons} \cdot 6.67 \frac{\text{dollars}}{\text{gallon}} = \$\,2.01$$

Transverse Seam Epoxy

The model calculated the volume of epoxy used to seal the transverse seam using Equation H.12. Since there were no transverse seams in the jacket, the volume (in gallons) of epoxy required for sealing the transverse was zero gallons, and obviously, the cost was also zero.

$$\text{transeam}_{\text{volume}} = \frac{\text{jacket}_{\text{length}} \cdot \text{transeam}_{\text{number}} \cdot \text{conversion}_{\text{length}}}{\text{epoxy}_{\text{productivity}}} \qquad (\text{H.12})$$

$$\text{transeam}_{\text{volume}} = \frac{72 \cdot 0 \cdot \frac{1}{12}}{40} = 0.0 \text{ gallons}$$

$$\text{trans. seam epoxy cost} = 0.0 \text{ gallons} \cdot 6.67 \frac{\text{dollars}}{\text{gallon}} = \$\,0.0$$

Jacket Fasteners

The number of fasteners was calculated using Equation H.13:

$$\text{fastener}_{\text{number}} = \text{integer}\left(\frac{\text{jacket}_{\text{length}}}{\text{fastener}_{\text{spacing}}}\right) \cdot \text{longseam}_{\text{number}} +$$

$$+ \text{integer}\left(\frac{\text{jacket}_{\text{periphery}}}{\text{fastener}_{\text{spacing}}}\right) \cdot \text{transeam}_{\text{number}} \qquad (\text{H.13})$$

$$\text{fastener}_{\text{number}} = \text{integer}\left(\frac{72}{4}\right) \cdot 2 + 0 = 36$$

The default unit price used in the model for the jacket fasteners was provided by expert knowledge as \$0.24 per fastener (Snow 1999).

$$\text{Fasteners cost} = 36 \text{ fasteners} \cdot 0.24 \frac{\text{dollars}}{\text{fastener}} = \$\,8.64$$

Jacket Fabrication

According to expert knowledge (Snow 1999), a lump sum fee was charged to each project to account for the cost of the mold used to fabricate the jackets. The default cost was $610.00 (Snow 1999).

$$\text{Jacket fabrication cost} \quad = \frac{610\ \text{dollars}}{4\ \text{jackets}} = \$\,152.5/\,\text{Jacket}$$

Labor

Labor fees, which included senior technician fees and one worker, were calculated as a percentage of the total linear footage of repair, but not less than one man-day (Snow 1999) The total footage of repair for the Gandy Bridge was 24 feet (4 jackets 6-feet long each), 10 percent of which was 0.24 man-days. Thus, one man-day was used. The default unit price used in the model for a senior technician was $450.00 per one man-day. Similarly, the default unit price used in the model for a worker was $150.00 per man-day. Labor fees were evenly divided among the number of jackets.

$$\text{Senior technician cost} = 1\ \text{day} \cdot 450\frac{\text{dollars}}{\text{day}} \cdot \frac{1}{4\ \text{jackets}} = \$\,112.5/\,\text{Jacket}$$

$$\text{Worker cost} = 1\ \text{day} \cdot 150\frac{\text{dollars}}{\text{day}} \cdot \frac{1}{4\ \text{jackets}} = \$\,37.5/\,\text{Jacket}$$

Cathodic Protection Specialist

This item included fees charged by a CP specialist while inspecting the jackets after the repair was completed. A lump sum equal to $2500.00 was evenly divided among the number of jackets.

APPENDIX M

QUANTITY COMPUTATION BOOK FOR THE GANDY BRIDGE REPAIR PROJECT

Data generated by the parametric quantity model was compared to the following documents from the Quantity Computation Book of the FDOT Financial Project 404106-1-52-01:

- Engineer's Estimate (FDOT (k))
- CP Jackets with Sacrificial Anode Mesh, FDOT Pay Item 2400-142-4 (FDOT (l))
- CP Bulk Zinc Anode, FDOT Pay Item 2455-81-101 (FDOT (m))
- Concrete Repair and Reinforcement Repair, FDOT Pay Items 2401-70-4 and 2415-1-4 (FDOT (n))
- Contingency Item, FDOT Pay Item 2457-70-35 (FDOT (o))

The above documents are not releasable since 9/11/2001 based on Florida Statute 119.07 (3)(ee). Documents are on file in researcher's office and FDOT.

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